Chapter 7
Mixed-Species Plantings

> In developing forest culture, rather than controlling the species genes and the population structure, farmers have chosen to retain and manage the diversity of species, structures and functions inherent to local forest ecosystems. To the question, 'Why did you choose this model rather than monocrop forestry?' (Indonesian) farmers respond by asking "Why should we choose monocrop forestry rather than our diversified model"
> Indonesian farmers discussing their agroforests;
>
> Michon (2005, p. 163)

> Endeavours to establish pure stands everywhere is based on an old and highly detrimental prejudice …Since not all tree species utilize resources in the same manner, growth is more lively in mixed stands and neither insects nor storms can do as much damage; also, a wider range of timber will be available everywhere to satisfy demands …
> German silviculturalist von Cotta (1828) quoted by Pretzsch (2005, p. 42)

Introduction

The third way in which forests might be re-established (and the second way in which degraded land might be replanted) is to use multi-species plantations or polycultures. As was the case with monocultural plantations, these plantings are usually undertaken when natural regeneration is thought to be unreliable or when species with having particular economic advantages are required. Mixed-species forests are not half-hearted attempts to mimic the diversity present in natural forests but they do seek to take advantage of some of the functional advantages of species-rich natural systems including their capacity to use resources more efficiently and to reduce nutrient losses from the system.

Landholders using mixed-species plantations are usually aiming to generate a wider range of goods or ecosystem services than provided by simple plantation monocultures and any increase in plant biodiversity is mostly incidental to this objective. Plantations established to provide goods are commonly felled at some point but those used to generate ecosystem services may remain undisturbed. Examples of the former are those that include, perhaps, timber trees and fruit trees

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while examples of the latter are the multi-species plantings established to stabilize heavily degraded sites such as former minesites. Depending on circumstances, the numbers of tree species used in mixed-species plantations might be small or large and may include exotic species as well as native species. According to the terminology discussed earlier, the approach represents a form of forest rehabilitation.

Mixed-species plantings are not widely used in industrial plantations because they are more difficult to manage than simple monocultures. Nonetheless, foresters have long been interested in their potential advantages (Wormald 1992; Pretzsch 2005). Trials can be found throughout the tropics and continue to be established. Unlike industrial tree-growers, smallholders have always had a more pragmatic attitude to polycultures and their agroforestry systems commonly use a variety of tree species. Again, this is not because of any particular desire to conserve biodiversity but because mixtures suit their ecological and economic circumstances and provide the goods they need while reducing their vulnerability to ecological hazards.

In recent years ecological researchers have renewed their interest in polycultures. At first this was because of an interest in the functional consequences of biodiversity loss. More recently their interest has being driven by questions about how ecosystems are assembled and the interactions between species with differing traits. Much of this research has involved laboratory studies and short-term field trials and there is a need for ecologists and silviculturalist to find ways of converting the results of these studies into more robust forms of reforestation that are applicable at a farm or landscape level and that take account of the economic drivers of reforestation.

This chapter begins this process by examining the silviculture of mixed-species plantings. After reviewing some of the potential advantages and disadvantages of polycultures it discusses different types of multi-species plantings at particular sites as well as mixtures at a landscape scale formed by spatial mosaics of simple monocultures. It then reviews some of the implications these silvicultural designs have for the provision of ecosystem services.

Some Potential Advantages of Mixed Species Plantations

Mixed-species tree plantations offer a number of potential advantages. These include the possibility of increasing stand productivity, improving the nutrition status, improving resistance to pests and diseases and generating various important financial benefits. And, as more species are used, the ecosystem is likely to gain some degree of ecological and economic resilience. None of these benefits are assured and their development depends on the types of species and mixtures used and on the environmental and economic conditions present. In some situations mixtures may also be a way of ameliorating site conditions making it possible to establish preferred species at sites at which they might not otherwise have been able to grow (Table 7.1).

Table 7.1 Potential advantages of multi-species plantations

Advantage	Reason
Enhanced production	Greater niche complementarity between species; contrasting phenologies (separation in time) or root or canopy architecture (separation in space)
Improved nutrition	Greater ability to access and conserve nutrients leading to improved growth
Reduced damage from pests or disease	Susceptible tree species hidden in space or natural enemies of pests encouraged so damage is less
Improved financial benefits	Goods produced for several markets; greater flexibility in timing of cashflows
Site amelioration	Facilitator species modify site conditions to eradicate competitors and allow entry of preferred species

Enhanced Production in Multi-Species Plantations

There is increasing evidence that some multi-species plantations can have greater levels of productivity than monocultural plantations of their constituent species (Biot et al. 1995; Cannell et al. 1992; Forrester et al. 2006; Jones et al. 2005; Kelty 2006; Piotto 2008). The phenomenon has been recognized for some time and has been widely studied with grasses and agricultural crops (Harper 1977). Much of this early work addressed the nature of above- and below-ground competition and explored situations where inter-specific competition between two plant species might be less than any intra-specific competition among plants of the same species growing at the same density. These studies were done in so-called replacement series by exchanging plants of one species with those of another thereby creating a mixture. Harper described the Relative Yield as being the ratio of the yield of a species in a mixture to that of the species growing in a monoculture at the same density. In a 50:50 mixture a Relative Yield of 0.5 shows that the growth of that plant species was the same in the mixture and the monoculture. A Relative Yield of >0.5 showed it grew better in the mixture than in a monoculture while a value <0.5 showed it was adversely affected by growing in a mixture. The Relative Yield Total is the sum of the Relative Yields of all species in the mixture. When this is >1.0 the overall productivity of the mixture is better than that of either monoculture. The majority of these agricultural studies involved simple mixtures involving only two species. Joliffe (1997) reviewed the agricultural literature dealing with mixtures and found that, on average, mixed plantings had 12% more biomass than monocultures but gains of up to 30% were observed in some studies.

In recent years the topic has attracted additional attention because of the on-going reduction in global biodiversity. This renewed interest has focused on the question of the functional importance of this biodiversity loss. The problem has been addressed in two ways; some have explored the effect of progressive biodiversity

losses from natural ecosystems while others have been more concerned with how ecological processes might change as more species are added to an ecosystem. Most of these studies have involved more than the two or three species commonly used in the earlier agricultural experiments. Much of this experimentation has been carried out in simple laboratory microcosms or in agricultural lands using grasses or herbs and very few studies have been done over long time periods using tree species. Nevertheless, some broad conclusions are beginning to emerge. These have been extensively reviewed by Hooper et al. (2005). Among these conclusions are (i) that certain combinations of species are complementary in their patterns of resource use and can increase the net primary productivity and degree of nutrient retention in a ecosystem over that provided by a single species, and (ii) that more species are required to ensure a stable supply of goods and services over the longer term and as larger areas are considered. This is because species respond differently to different environmental perturbations and stresses. However (iii), it is the functional characteristics of the species involved as well as the number of functional groups present that is important in influencing ecosystem properties rather than taxonomic diversity per se. The significance of differences in species diversity in higher trophic levels remains unclear.

Plant communities are often thought to be largely structured by inter-specific competition and the success of one species occurs at the expense of another. But two other mechanisms potentially able to improve the overall productivity of species mixtures are facilitation and complementarity. Facilitation occurs when one species increases the availability of a resource to others and thereby benefits the growth of those other species. An obvious example of this is when a nitrogen-fixing species is grown a mixture with other non-fixing species in an infertile soil. In these situations the nitrogen fixer is able to add nitrogen to the ecosystem and so reduce this limitation on the growth of the other species. Note that the beneficial role of this particular facilitator would disappear on more fertile soils where growth is not being limited by nitrogen availability. Another form of facilitation is when a tolerant species grows in the open and provides shelter or shade enabling another, less-tolerant, species to become established and grow at that site. Specific examples of facilitation will be discussed further below.

The second mechanism, complementarity, arises when species having different ecological niches are grown together. In this case niche partitioning reduces inter-specific competition and greater productivity is possible because, collectively, the species are able to use the resources at a site more efficiently than if only one species was involved. The significance of this is greatest when one or more of these resources are limiting for plant growth. So, for example, a productive mixture might be one which included a relatively shade-intolerant species with a sparse crown growing with a relatively shade tolerant species with a denser and deeper crown. The canopy would be stratified with the more shade intolerant species forming the upper canopy allowing sufficient light through to sustain the slower growing and shade-tolerant species in a sub-dominant position (Fig. 7.1). The mixture captures more light than either species would if growing in a monoculture. As noted in the previous chapter, many monocultures often colonized by dense understories

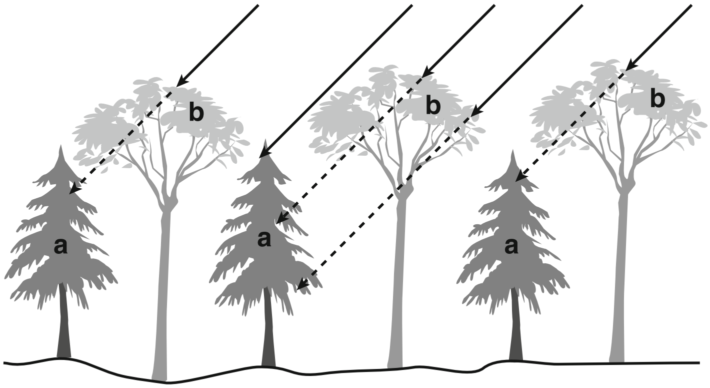


Fig. 7.1 Stable mixtures often have species with complementary attributes growing in stratified canopies. This mixture contains a shade tolerant species (**a**) and a shade intolerant and open-crowned species (**b**). Species (**a**) gets direct radiation in its upper crown as well as indirect radiation that penetrates he crowns of species (**b**). This allows **a** to persist in a sub-dominant position

because of the light able to penetrate the upper canopy layer. Although the shade-intolerant species is likely to be faster-growing than the shade tolerant species, at least initially, the growth rates should not be too different in order to prevent one species dominating and out-competing the other(s). In any case, Smith (1986) suggests the overstorey should not comprise more than 25% of the total number of trees. This allows space for the crowns of the dominant species to expand while the lower canopy trees help reduce branching in the stand dominants and provide what Smith (1986) refers to as a 'trainer' effect.

Other plant attributes enabling some complementarity would be differences in foliar phenology (e.g. deciduousness), root growth phenology or in rooting depths. A spatial separation in rooting depth with one species having only shallow roots while another has only deep roots is unlikely but examples have been found where one species in a has deeper roots than another which could allow some differentiation in patterns of soil resource usage (Ewel and Mazzarino 2008; Lamb and Lawrence 1993). Competition between species with differences in these attributes is reduced because they use resources at different times or from different spatial locations.

It is important to note that static measures of complementarity such as these can change over time and species once regarded as complementary can sometimes become competitive. Ewel and Mazzarino (2008) grew a palm (*Euterpe oleracea*) and a large herb (*Heliconia imbricata*) in mixtures with each of the trees *Hyeronima alchorneoides, Cedrela odorata* and *Cordia alliodora*. The first of these tree species is an evergreen but the other two are deciduous trees. The three tree species initially dominated their respective mixtures but over time a difference emerged in the way the two deciduous species and the evergreen species interacted with the palm. In the former the palm was able to take advantage of the period of deciduousness and grow up and join the canopy layer. The difference in leaf phenology gave the palm

a competitive advantage even though all species had initially shared the site's resources. Eventually its intrusive growth allowed it to out-compete the trees and dominate the canopy. As a result, the trees died and net primary productivity declined. In the mixture involving the evergreen tree the palm also grew up and joined the canopy. But, in this case, overall productivity was enhanced compared with a nearby tree monoculture and the palm appeared to play the role of a complementary species rather than a competitive species, probably because of a difference in nutrient acquisition strategies.

Changes in site conditions can also modify competitive relationships (Pretzsch 2005). The theoretical cause is shown in Fig. 7.2. In the first case (Fig. 7.2 upper) the two species have similar niche requirements although they differ in their productivity at this particular site. A mixture of the two would not cause an increase in stand productivity because they would be competing for the same resources at the same time and A would out-compete B. A different situation prevails when the two species have different ecological niches (Fig. 7.2 lower). In this case the two species are mixed in stands at four different locations along an environmental gradient (e.g. in soil fertility or rainfall). The site conditions at location 1 are optimal for species A but are only marginally suitable for species B. In this case a mixture of the two would have no advantages because the growth of B would be poor. At location 2, however, the site conditions are suitable for both species and a mixture

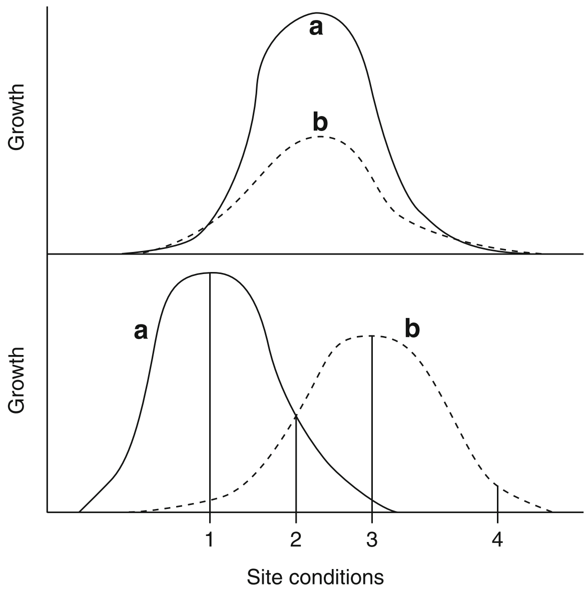


Fig. 7.2 Site conditions affect competitive interactions and the productivity of mixtures. In the upper diagram both species have similar site tolerances but (**a**) is more productive than (**b**) and the mixture would fail. The *lower diagram* shows the growth of species mixtures planted at four sites along an environmental gradient. Each species has different site tolerances. At site 1 species (**a**) grows well but conditions are marginal for (**b**). At site 2 conditions allow (**a**) and (**b**) to grow. At site 3 species (**b**) grows well but conditions are marginal for (**a**). At site 4 conditions are marginal for (**b**) but unsuitable for (**a**) (After Pretzsch 2005)

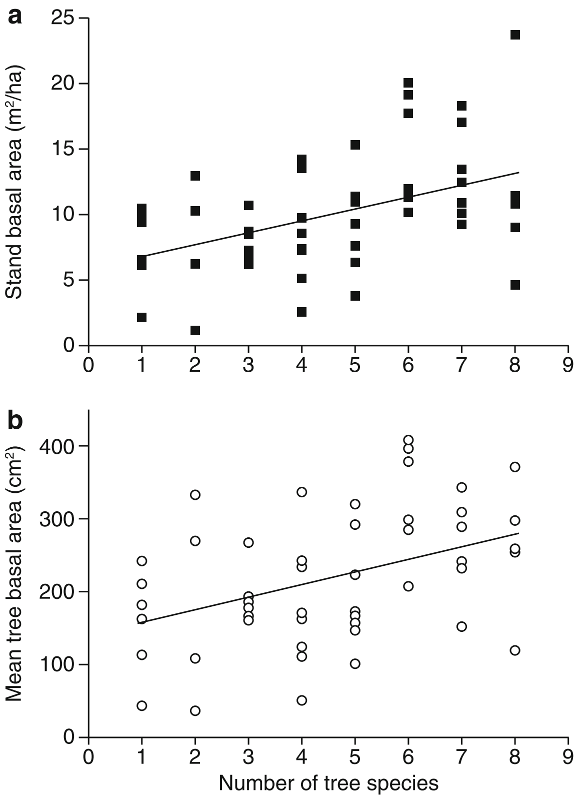
could be advantageous. At locations 3 conditions are optimal for species B but are marginal for species A; again a mixture here would have no advantages. At location 4 the conditions are only marginal for species B and are unsuitable for species A and it would soon disappear.

These models prompt two questions. The first is – what are the site preferences of potential plantation species? The second is – how much of each site type is available for reforestation and where might conditions be favourable for mixtures of particular species? Most tropical reforestation programs probably commence without enough knowledge to answer either question with any great confidence. Pretzsch (2005) argues that, in such cases, mixtures can be a way of redistributing risk and avoiding complete plantation failure.

Much of the research done on the relationships between diversity and productivity has been carried out in laboratories or in field experiments with grasses or shrubs that have only lasted a short period of 1 or 2 years. One of the few studies of the effects of increasing levels of tree diversity on productivity over a long period was that carried out by Erskine et al. (2006) who examined the growth of trees in 53 mostly multi-species plantations established on former farmland in the humid tropics of northern Australia. The plantations contained between one and eight species and were 6–9.5 years old when assessed. The composition of each plantation was largely a random assemblage although all species were commercially valuable timber trees. A total of 27 species were used across the various plantations and these included gymnosperms and angiosperms as well as some potential nitrogen fixers. Each plantation was at least 2 ha in size and had trees planted at densities of 600–800 tph. The study found evidence that increasing species richness (up to eight species) was associated with increased levels of productivity as measured by stand basal area or mean tree basal area (Fig. 7.3). A linear relationship was found between the number of tree species in each plantation and productivity but it was not clear that this would persist if more than eight species were used. Although the study design did not allow the underlying casual mechanisms to be identified there was some evidence that complementarity (associated with differences in canopy architecture) was involved but no evidence that any of the putative nitrogen fixers had improved productivity when included in the mixtures.

Contrasting results were obtained from another study in the same region suggesting that other mechanisms can also operate (Firn et al. 2007). This study involved mostly older (>65 years) plantations originally planted as monocultures. The species included well known native timber trees including two angiosperms, *Flindersia brayleyana* (Rutaceae) and *Toona ciliata* (Meliaceae) as well as two gymnosperms, *Araucaria cunninghamii* (Araucariaceae) and *Agathis robusta* (Araucariaceae). Each plantation was planted in close proximity to the others and all were on the same fertile, basalt-derived soil. The plantations were surrounded by nearby natural rainforest and, as a result, all were colonized by additional trees species. Sufficient time has passed for a number of colonists from the surrounding natural forests to grow up and join the canopy layer (see example in Fig. 6.11). At the time of the study, the richness of overstorey tree species (>10 cm dbh) in the former monocultures ranged from one to 17 species per 0.1 ha plot. Although additional

Fig. 7.3 Relationship between tree species richness and productivity (basal area) of (**a**) stands and (**b**) mean trees in stands of randomly assembled mixtures at age 6–9.5 years growing in northern Queensland, Australia (**a**: Stands: $N=53$; $r^2=0.21$; $p=0.001$; **b**: Mean tree: $N=53$; $r^2=0.18$; $p=0.001$). Each plantation >2 ha and stand densities were 600–800 tph (After Erskine et al. 2006)



trees were colonised the planted stands the overall tree density (trees >10 cm dbh) in the various sites was still broadly similar and ranged between 500 and 770 tph. The relationship between the species richness at the time of assessment and stand productivity is shown in Fig. 7.4. In this case, rather than production increasing with species richness, the reverse appears to be true. This is probably a result of the 'sampling effect'. This occurs in situations where one of the species included in a mixture happens to be particularly efficient in resource usage. In such cases most of the overall plantation productivity is derived from this species and not from the greater collective efficiency of the community. Each of the timber species originally established in these plantations were known to be highly productive plantation species and the additional species have not be able to contribute much additional productivity, at least until now.

Although the review by Hooper et al. (2005) highlighted the importance of functional groups in mixtures it is difficult to say much about the number of functional groups used in either of these two studies. Most can probably be classified as shade-intolerant long-lived secondary species although the variety of plant families represented suggest there may be some physiological and niche differences as well. The results suggest there is scope for increasing overall

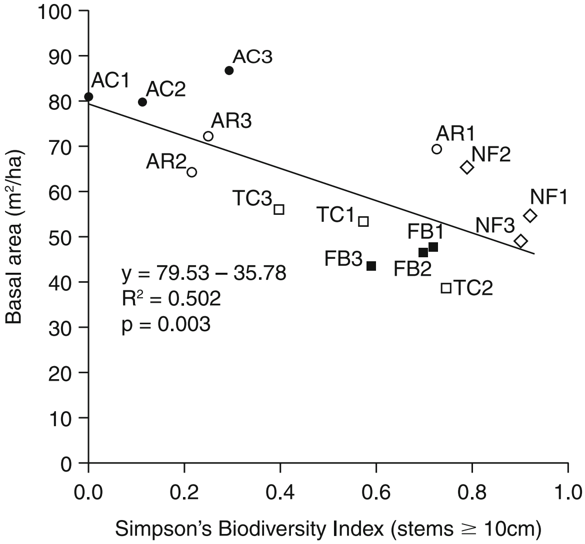


Fig. 7.4 Relationship between tree biodiversity in 0.1 ha plots and production (basal area) in old (>50 years) former monocultural forests in which natural regeneration from nearby secondary rainforest has added additional trees to the canopy layer. AC=*Araucaria cunninghamii*, AR=*Agathis robusta*, TC=*Toona ciliata*, FB=*Flindersia brayleyana* and NF=Natural Secondary Forest (Firn et al. 2007)

plantation productivity by using mixtures of several tree species with complementary traits. But they also show that great care is needed in deciding the composition of the mixture, the numbers of species to use and in the relative proportions of each species in the mix if any gains are to be worthwhile and of practical significance. It is also important to remember that species are not necessarily equally valuable and any gains in production need to be accompanied by gains in overall economic value if mixtures are to be attractive to forest growers. Some of these additional design issues will be discussed in more detail below.

Improved Nutrition

A second potential advantage of mixtures is that they may improve the nutritional status of a plantation beyond that occurring in monocultures. This might be done by increasing the amounts of nutrients entering the ecosystem, limiting impediments to nutrient cycling within the system or by reducing nutrient losses from the system. As before, facilitation and complementarity are important mechanisms by which these changes can occur.

One of the most widely studied situations is that where a nitrogen fixer is included in the mixture to increase the nitrogen stored in the ecosystem and improves the nitrogen nutrition of other species when their litter and roots decompose. There is now strong evidence that such mixtures can improve overall plantation productivity at sites with less fertile soils where nitrogen is limiting for plant growth (Binkley 1992; Forrester et al. 2006; Khanna 1998; Rothe and Binkley 2001). Some care is needed in mixing nitrogen fixers with other species to avoid one species from

out-competing the other. Where the nitrogen fixer is the more vigorous species the problem may be avoided if the nitrogen-fixer is short-lived or it can be thinned to allow the more commercially valuable species to grow unhindered in the improved soil. If the non-nitrogen fixer dominates the stand and suppresses the fixer it may receive an advantage because the stand density has been reduced. This benefit may exceed any advantage attributable to changes in nitrogen nutrition (J. Ewel, personal communication, October 2009). Mixtures including nitrogen-fixers will have no advantages at sites with soils with adequate supplies of nitrogen and the productivity of the more commercially important species may even decrease at such sites due to competition if the nitrogen-fixing trees are growing vigorously.

A number of tree species are thought to able to fix nitrogen under appropriate conditions. In the Asia-Pacific region these include species of genera such as *Acacia, Falcataria, Gliricidia, Leucaena* and *Sesbania* as well as species of the non-legumes *Casuarina* and *Parasponia*. The amounts of nitrogen these species might fix can exceed 200 kg ha^{-1} $year^{-1}$ (Khanna 1998) although the actual amounts are usually much less than this. The rates of fixation depend on site conditions (particular the available phosphorus levels) as well as the degree of nodulation, tree density and age. Depending on the nutrient status of these other species, the additional nitrogen may enhance their growth, especially if the additional nitrogen is provided at an early stage of plantation growth. Or changes in the ratio of foliar N/P may accentuate any limitation on growth caused by phosphorus (Siddique et al. 2008). In such cases phosphorus fertilization may be needed to capture the full advantage from using the nitrogen fixer. Other ways mixtures might increase the supply of nutrients other than nitrogen to the active nutrient cycle is if one of the species has root systems able to access refractory or less-accessible soil nutrients such as phosphorus. This might be done with particular mycorrhizal associations, by changes induced by activity in the rhizosphere of certain species (Khanna 1998) or by roots able to explore deeper soil horizons and thus act as 'nutrient pumps' that sustain shallower-rooted species in the plantation mixture.

Evidence concerning the effect of mixtures on nutrient cycling within forests is equivocal. The quantities of nutrients cycled through litterfall can be higher in mixtures involving nitrogen-fixing trees than in monocultures of the non-nitrogen fixing species (Rothe and Binkley 2001; Forrester et al. 2006). However, the rates at which these litters subsequently decompose appear to vary a good deal. Some studies report enhanced decomposer activity in more diverse ecosystems (Balvanera et al. 2006) while others find no effect or even that decay rates are slowed (Rothe and Binkley 2001). It is generally agreed that the rate of litter decay is largely influenced by litter quality and by the types of soil fauna that are present. Both are consequences of the particular species producing the litter and any mixture effects may be more a result of these factors and not tree species richness. In the case where nitrogen fixers have been used, the subsequent rates of soil nitrogen mineralization appear to be greater in mixtures than in pure stands (Khanna 1998). The amounts of particular nutrients being cycled might also be affected by complementary differences in the timing of nutrient uptake.

The role of mixtures in limiting nutrient losses from new forests is barely studied. This is despite the fact that leaching losses can be high, especially in young plantations, because of the often high rainfall intensities experienced in tropical areas. Leaching losses are reduced and nutrient retention is increased by the presence of dense root systems that intercept and immobilize ions being moved through the soil, especially if these belong to fast-growing species. However, there have been surprisingly few studies of rooting systems in different types of young plantations or in regrowth forests. One study reported by Berish and Ewel (1988) compared root development in agricultural and forestry monocultures, natural successional vegetation, the same regrowth vegetation enriched with additional species and a diverse multi-species community that sought to mimic a natural succession. Fine root densities were much higher in the species-rich communities than in the short-lived agricultural monocultures but the tree monoculture quickly acquired a root density similar to that of the species-rich successional vegetation. Studies of nutrient movement in the soils supporting the various treatments showed nutrient losses were high under the agricultural crops but that nutrients were conserved with perennial vegetation irrespective of species richness (Ewel et al. 1991). In this case the addition of more species did not enhance nutrient retention. But even if the tree monoculture had been less effective, most plantations (with the exception of species like teak) soon acquire a diverse understorey containing a variety of life forms including grasses, herbs and shrubs, irrespective of whether a tree monoculture or mixture is established. Because of this, nutrient losses are probably limited after the first few years. Nutrient losses are also limited when overall plantation productivity is high since nutrients are rapidly taken up and immobilized in biomass.

In summary, plantation mixtures including nitrogen fixers may have improved supplies of nitrogen and improve the growth at sites where nitrogen would otherwise be limiting. There may be other nutritional advantages arising from mixtures but the circumstances under which these occur have been poorly studied.

Reduced Damage from Pests and Diseases

It is widely believed that monocultural crops are more susceptible to pests and diseases that diverse natural ecosystems, especially when these crops are even-aged and cover large areas. If so this could be because monocultures lack most of the trophic complexity and controls such as predators found in natural ecosystems. In addition they offer a large food resource to any insect and pathogen species adapted to use them. Their narrow genetic base and the closeness of plants are thought to allow rapid colonization and spread of pests or infection. Crops of single species also lack the physical or chemical barriers to insect movement often found between plants in natural ecosystems. Some of these problems were discussed in Chapter 5 in the context of the vulnerability of monocultures to pests and diseases.

There is some evidence supporting the view that diversity does, in fact, reduce pest and disease problems. Jactel et al. (2005) carried out a meta-analysis of over 50 field studies and found that insect pest damage is greater in single species stands than in mixtures containing these same species. They concluded this was because pests had poorer access to the host trees, there was a greater impact by natural enemies or the pests were diverted from less susceptible to more susceptible species. Similar conclusions were drawn by Nair (2007). In the case of diseases Pautasso et al. (2005) reported that tree diversity may also make forests less susceptible to fungal pathogens. A particularly striking example of how crop diversity and spatial patterns could significantly reduce damage from disease comes from southern China. This was a large-scale (3,300 ha) study carried out with rice in Yunnan province. Rice in this area is affected by a rice blast fungus (*Magnaporthe grisea*) and the use of fungicide is common. But Zhu et al. (2000) were able to demonstrate that disease-susceptible rice varieties planted in mixtures with resistant varieties had 89% greater yield and the disease was 94% less severe than when a simple monoculture was used. The result was so striking that farmers participating in the study were able to give up the use of fungicides. Wolfe (2000) suggested this result points to a need to rethink the trend in agriculture which is leading to not only a reduction in the number of crop varieties but also to a diminution in the genetic variation within these varieties. He suggested it might even be time for agriculturalists to explore using species mixtures in some situations as well. There is no reason to see why these same conclusions should not apply equally well to forest plantations.

But some qualifications are needed. Firstly, populations of polyphagous insects and generalist pathogens can first build up on a preferred host species and then spill over onto less palatable species growing nearby leading to contagion (Jactel et al. 2005). Blanton and Ewel (1985) observed a similar phenomenon with leaf cutting ants. This suggests simple mixtures may be only able to limit, but not prevent, insect damage. In some cases they may even confer associational susceptibility. Secondly, these types of studies are yet to generate specific silvicultural guidelines to improve plantation designs. Just how much plant diversity is needed? Would alternate row plantings of two species provide any benefit or must the host tree be 'hidden' amongst a much greater variety of other taxa? And at what spatial scale should the mixture occur? Might a patchwork mosaic of monocultures be sufficient or must a more intimate tree-by-tree mixture be used? Sometimes these questions can be answered when the biology and behavior of a specific insect pest is known but it is very difficult to develop generic prescriptions to deal with unknown future insect pests. For this reason few plantation managers are likely to move to mixed species stands simply to reduce insect damage although they may be happy to accept that mixtures may provide some insurance value, especially against indigenous pests or diseases.

Financial Benefits

Mixed-species plantings are more expensive to establish and manage than simple monocultures and are likely to be less attractive to large industrial growers for this reason. But they do have some distinct financial benefits and for many

smallholders these financial benefits may be the most persuasive factor leading them to change from monocultures to mixtures. One advantage of mixtures is that they can offer a diversity of products such as different quality timbers suited for different markets or NTFPs as well as timbers. When future markets and prices are uncertain then diversifying products and income sources is a way of building economic resilience and is likely to appeal to smallholders aware of their commercial vulnerability. The disadvantage, of course, is that financial returns are reduced in situations where a large market develops for a particular product. In this case a mixed-species plantation reduces the amount of that particular good that can be sold by an individual producer. Some growers such as those acting as out-growers for large industrial enterprises are in the fortunate situation of being confident about the market they will supply and will willingly forego diversity. But many farmers are not in this position. In this respect it is interesting that households who acquired eucalypt plantations from village cooperatives during the doi moi period in Vietnam were often observed then inter-planting these monocultural plantations with species such as *Acacia auriculiformis, Styrax tonkinensis* and *Manglietia glauca* as a means of diversifying their income sources (Fahlen 2002). They evidently felt the advantages of diversity outweighed the disadvantage of not maximising their returns from growing a single crop of eucalypts. Other smallholders across the region have taken a similar view (Nibbering 1997; Pasicolan et al. 1997).

A second potential financial advantage of mixtures is that some designs can overcome one of the main disincentives to tree-growing by generating an early cashflow. There are several ways this might be done. One is by including faster-growing species that can be harvested at an early age with slower-growing species that make up most of the plantation. Another would be to include multi-purpose tree species able to supply, for example, fruit, nuts or resins from an early age. Or, finally, non-tree species supplying food or other products could be grown in the understorey as temporary or permanent components of the plantation. Complementarity is involved in both cases. But it is a form of economic and not ecological complementarity that generates these advantages.

Ameliorating Site Conditions at Cleared or Degraded Sites

The conditions at many degraded sites are such that only a small number of species – sometimes mostly exotic species – may be able to grow there. These conditions may be associated with infertile soils, aggressive weeds, high solar radiation levels or some other micro-environmental condition. By first planting a tolerant species these adverse environmental conditions are changed and the site can become suitable once more for a much wider range of species. Under ideal circumstances these species would have a modest market value and create a financial asset at the same time they were modifying the site's environmental conditions.

Amelioration might be achieved in two ways. One way would involve growing a species such as a nitrogen-fixer and then removing it once soil conditions had been improved. The facilitator would then be replaced by the preferred species.

Another way would be to use the facilitator as a nurse crop and growing the preferred species beneath it's canopy cover. In this case the benefit comes from the changed aerial micro-environment. Care is obviously needed to ensure the species in the mix are also complementary and that the nurse species does not act as an inhibitor. This could be achieved by choosing nurse trees having sparse crowns or by planting these at low densities. In many cases where this approach is used the nurse species is removed after a few years once the preferred species has become established. The approach has been used with agricultural crops such as coffee (hence 'shade coffee'). The idea of protective nurse trees also forms the basis of some silvicultural systems such as the Shelterwood method (Smith 1986).

The potential advantages of mixed species plantings come at a cost. The more species being used the more complicated the management and, until recently, few large industrial tree-growers have seen the advantages being sufficient to overcome the disadvantages. But this appears to be changing and it is interesting that some of the world's most efficient and best-managed timber companies in northern Europe are beginning to explore using simple mixtures in order to enhance production and biodiversity (Berqvist 1999; Fahlvik et al. 2005; Mönkkönen 1999; Pretzsch 2005).

Species Functional Types

What types of species should be used in mixed-species plantings? At least one of them must have a significant subsistence or commercial value to attract a land-owner's interest. And in many situations some may need to be capable of a facilitative role such as nitrogen fixing to ensure the plantings are established and grow. But, where complementarity is critical for the success of the mixture, the various species will need to belong to different functional types and have traits that complement each other. There is still some uncertainty concerning how different functional types might be classified. Wilson (1999) thought there were two basic types. The first were species that shared the same environmental conditions and hence were likely to be found together. The second were those that used the same resources and, thus, were unlikely to be found together because of competitive exclusion. Noble and Gitay (1996) identify five possible ways in which functional types might be classified:

- Phylogeny – groups of taxa with similar evolutionary histories.
- Life form or structure – groups of taxa with the same life form.
- Resource use – taxa using the same resource(s).
- Response to a defined perturbation – taxa that have a similar response to changed environmental conditions.
- Role in ecosystem function – taxa having similar patterns of resource use or biochemical function (e.g. nitrogen fixation).

Recent research on functional types has been largely carried out by those seeking to model the dynamics of existing forests. In these situations phylogeny appears not to have been highly valued although it may reflect important functional attributes such as basic physiological properties or resistance to certain pests. Instead, rather more effort has been undertaken exploring the other four categories. Thus Ewel and Bigelow (1996) argued function follows form and that the diversity of life forms present defines the way a forest can function. Likewise Köhler et al. (2000) used resource usage and differentiated species types according to their tolerance of shade tolerance and height at maturity. Ashton et al. (2001) developed a similar classification based on successional types that recognized pioneers of stand initiation, pioneers of stem exclusion, late successional dominants, late successional non-dominants, late successional sub-canopy and late successional understorey. Noble and Gitay (1996) found tolerance of fire was a useful way of classifying species while Gitay et al. (1999) and Gourlet-Fleury et al. (2005) explored the use of classifications based on growth rates and longevities. The variety of plant traits represented here include differences in stature, longevity, shade tolerance, growth rate and the architectural characteristics of canopies and roots. These, together with differences in growth phenology, offer scope for finding species combinations forming complementary partnerships.

In overcoming land degradation, one of the tasks is to develop ecosystems that are resilient. Students of resilience argue it is promoted by not only having species from a variety of functional types but also having multiple representatives from each type (Diaz and Cabido 2001; Elmqvist et al. 2003). But it may not be the diversity of functional types that is important. Rather, it may be that new forests need to have a certain combination of functional types to deal with the particular environmental conditions at a site. Perhaps a better way of addressing the issue might be to ask what functional types should be present that enable a particular new forest to cope with the ecological and economic circumstances that might be present over, say, the next 40 years? This period is the time frame in which managers might operate and during which various environmental stresses might develop. In this case the functional groups might include:

- Species for production: short and long-lived trees (all of which have some market value); shade-tolerant and shade-intolerant species able to occupy different positions in the forest canopy.
- Species able to reduce nutrient stress: species with high nutrient use efficiencies and using various mycorrhizal symbionts; deep-rooted species able to explore soil profiles as well as shallow-rooted species able to capture nutrients recently cycled through litter layers; some species capable of nitrogen fixation.
- Species able to tolerate occasional water stress: deep rooted species able to tolerate seasonal droughts and deciduous or semi-deciduous species.
- Species able to tolerate fire: species with thick, heat resistant barks and/or species able to resprout after fire.

The list includes those affecting ecosystem functioning (because of the way they access resources such as light, nutrient or water) as well as others that differ in the way they respond to disturbances (such as fire or drought). But the new forests should also play a role in sustaining regional biodiversity and so include species able to sustain mutualistic partnerships with wildlife, especially those able to disperse seed. Some species will have traits that place them in several of these categories. Not all of these will be equally relevant in every location and it should be possible to fine-tune the list and target the more appropriate traits according to the environmental conditions present now or likely to develop in future.

Although this suggests a way of identifying target species to use in mixtures commercial growers must also find ways of linking these functional types with the landowner's evolving economic circumstances. In some cases the combination might not be too difficult to imagine. For example, a fast-growing tree able to be sold after only a few years as a utility timber might be grown together with a slower-growing species able to produce a specialty timber but needing a longer growing period. Likewise it should be possible to find species providing NTFPs as well as timber amongst these various ecological groups. In developing mixtures for smallholder the over-riding task may have less to do with boosting productivity and more to do with satisfying the immediate and longer-term economic needs of the household. Various approaches to deal with this task are outlined below.

Designs for Mixed-Species Plantations

Some of the ways plantations might be designed to take advantage of the potential benefits of polycultures are outlined in Table 7.2. The Table is divided into two parts. The first part is concerned with four types of mixed-species planting that might be established at a particular site. Two of these are even-aged with all tree species being planted together at the start. The other two are uneven-aged with one or more of the species being planted below a nurse or cover crop once it has been established. Circumstances will dictate the actual numbers of species that might be involved in each mixture. The second part of the table concerns simple monocultures but is specifically concerned with the opportunities to foster diversity at a landscape scale by having a spatial mosaic of these different monocultures.

Cash Crop Grown Beneath a Timber Plantation

This is system is shown as Design 1 in Table 7.2. The purpose of the design is to generate an income from the site before the overstorey trees are ready to harvest. This helps reduce one of the major disincentives to tree growing experienced by smallholders. The mixture is initiated by first planting the overstorey trees. These might be a single preferred species or a mixture of several species. In either case the species chosen are

Table 7.2 Plantation designs involving mixtures

At individual sites				Across landscapes
Uneven-aged		Even-aged		Uniform age
Design 1	Design 2	Design 3	Design 4	Design 5
Trees and understorey crop	Trees only	Different rotation lengths	Single long rotation	Simple tree monoculture
NTFP species established beneath trees	Final crop trees under-planted beneath a temporary tree cover crop	Trees grown on short rotation mixed with others on long rotation	Permanent mixture of two or more species	Involving a single species or a spatial mosaic of monocultures with several species
Temporary mixtures			Permanent mixtures	

those needing rotations of more than 20 years before they can be logged for commercial purposes. Once the plantation trees are established and canopy closure has been achieved, the short-term cash crop is planted in the understorey between the rows of trees (unlike the well-known taungya system where the crops are planted at the same times as the trees and are abandoned once tree canopy closure occurs).

Some care is needed in selecting both the overstorey and understorey species to minimize competitive interactions and ensure they are complementary. The overstorey trees should have open-crowns that produce mottled light rather than a uniform shade. They should be able to produce useful timber or NTFPs, be able to develop straight unforked stems and be compatible with the crop (e.g. by having deeper roots). Other desirable attributes might include being capable of fixing nitrogen, being tolerant of heavy pruning or pollarding and being wind-firm. The understorey cash crop must be able to tolerate the environmental conditions in the understorey (both the light conditions and the degree of root competition) and be able to generate a financial return in a relatively short time. A perennial species able to produce successive harvests at frequent intervals would be especially attractive but one that could be harvested and then replanted might be attractive as well. The best species would also be one for which there is already some demand and an established market.

A number of such systems have evolved in agroforestry practices in various parts of Southeast Asia although few of these have been intensively studied. It is likely that some have been prompted by the declining availability of timber and NTFP supplies from natural forests while others are simply attempts to maximize the income from small areas of land using a system that requires little maintenance once it is established. These systems include food crops such as pineapples, bitter bamboo, cardamom, tea, ginger, lemongrass as well as traditional medicinal plants or rattans planted under plantations of timber species (Rao et al. 2004). In each case the amount of shade and numbers of trees vary according to the particular requirements of the understorey crop. Sometimes the trees are pruned or pollarded to help adjust light levels. Alternatively, light levels can be managed by planting

several rows of trees and leaving a belt up to 10 m wide before the next rows of trees for the underplants.

Mixtures of trees and rattans require some particular forms of complementarity. The rattans should not be so heavy that they distort their host trees. At the same time the trees used should not be those with long branchless boles such as species like *Eucalyptus deglupta* that make it difficult for the canes to access the canopy (Weidelt 1996). The numbers of rattans per tree should also be limited to avoid the canes becoming entangled and difficult to harvest (Fig. 7.5).

This design has the advantage of flexibility and a large number of species combinations is possible. Provided the cash crops grown in the understorey are not too big they are unlikely to hinder the growth of the trees. And, depending on the species used, the structural complexity of the new plantation could be more attractive to some wildlife than a simple tree monoculture although the overall plant species diversity is not likely to be very great. The primary disadvantage of the design is the need to identify complementary species. However, this may not be as much of a problem as it seems because continuous testing by farmers appears to have already generating many working examples of systems that form ecologically and financially successful combinations. Of course any thinning of the plantations trees may have some consequences for the understorey cash crop either because these plants are physically damaged or because of subsequent changes in environmental

Fig. 7.5 Design 1 (trees and an understorey crop) represented by rattan established in a young plantation in Laos PDR. In time the rattans will grow up into the canopy

conditions (although the new environmental conditions after thinning might allow other species to be used).

Case Study 1: Shade coffee

An example of under-cropping that is common throughout the tropics is the growth of coffee (*Coffea* spp.) beneath a tree overstorey. In most cases the trees are arranged to provide around 30% shade and the coffee is then planted beneath them at spacings of 3 m or less. Greater amounts of shade have been beneficial at more marginal sites (DaMatta 2004). A large variety of woody species have been used to provide the overstorey cover including species of *Casuarina, Erythrina, Falcataria, Gliricidia, Grevillea* and *Leucaena*. There are a number of variations to the basic model (Somarriba et al. 2004). So, for example, a broad mixture of tree species have been used in some locations to provide the overstorey shade and Philpott et al. (2008) provide examples from southern Sumatra. In such cases, tree management for, say, fruit production, may not lead to optimal shade conditions for the coffee. And sometimes the system has involved other food crops as well as coffee. A system in the highlands of Papua New Guinea evolved from one that planted Arabica coffee beneath an established *Falcataria moluccana* or *Leucaena leucocephala* canopy to one where coffee and *Casuarina* were planted into food gardens. In this case farmers modified the initial system which mostly produced just subsistence foods to pass to one dominated by coffee, bananas and *Casuarina oligdon* and, then finally, to a simple coffee and *Casuarina* system. This system provides food, cash, fuelwood and timber (Bourke 1985).

Coffee is grown without an overstorey tree cover in some places (and is referred to as 'sun-coffee'). Production levels can be higher but the system has a number of disadvantages (Somarriba et al. 2004; DaMatta 2004). There is a greater need for agrochemical inputs, sites are more prone to soil degradation and there is evidence of a biennial production cycle with a 'good' year being followed by a 'poorer' year. The longevity of the coffee plants also tends to be shorter when grown in full sun rather than shade. Farmers using this monocultural system are more exposed to risks arising from international price fluctuations while coffee grown beneath a tree cover provides famers with lower cost and a greater diversity of products to buffer income fluctuations. In short, sun coffee might be best suited to larger growers able to support the more intensive management but smallholders might do better with coffee grown with a tree cover crop, especially at less fertile sites. In this case the trees form a complementary mixture with the coffee but also act as facilitators to improve economic productivity.

Uneven Aged Plantations Involving Only Trees

This silvicultural system is represented by Design 2 in Table 7.2. It is similar to Design 1 in that it involves underplanting beneath an existing tree canopy. However,

it differs from Design 1 because the underplantings are also trees and these eventually go on to replace the overstorey species or 'nurse' trees that were initially planted. That is, the design represents only a temporary mixture. Its main purpose is to ameliorate otherwise unfavourable site conditions using a tolerant tree species to facilitate the establishment of a more preferred species. The nurse trees may exclude shade intolerant weeds (or at least make them easier to control), improve the soil or change some other properties of the micro-environment that are hindering the establishment of a preferred species.

The facilitator or nurse tree species should have certain attributes. They must be tolerant of a wide range of site conditions and be capable of rapid growth, at even degraded sites, such that a closed canopy is formed within a few years. The crown should be initially dense enough to hamper weeds but be not so dense that it also limits the growth of the preferred species. This means most nurse species will be from early successional stages and most underplanted species are likely to be from mid or later successional stages. Ideally, the nurse tree should acquire a commercial value at an early age so that its harvesting will yield a financial return. Otherwise it should be short-lived so that the preferred species can eventually grow up and replace it. If felling is done it should not damage the more valuable species growing in the understorey. This means that felling probably has to occur before the overstorey trees are very large.

The attributes of the under-planted species must have some degree of complementarity with the nurse species. In particular, they must be physiologically tolerant of some early shade and be not merely able to survive but to grow in height while the nurse trees are present. They must also be substantially more valuable than the nurse trees to persuade the landowner to bother with underplanting. Unless this is the case it would make more sense to simply use successive rotations of the nurse tree. Commercial worth would be one expression of value but ecological or conservational significance could be another.

Case Study 2: Improving conditions at a degraded site – Vietnam

Many coastal forest areas in central Vietnam have been highly degraded by past military activities. The Hai Van Pass area between the cities of Hue and Danang was affected in this way and became grasslands dominated by *Imperata cylindrica.* Although small scattered patches of natural forest remain nearby it was difficult for any of these species to regenerate within the degraded areas and attempts at plantings failed. The Phu Loc District Forest Protection Department has rehabilitated the area and established native species using a cover crop of *Acacia auriculiformis*. The first *Acacia* trees were planted in 1986 at densities ranging from 1,650 to 3,300 tph. These excluded the grasses and other weeds and probably added nitrogen to the soils (although the extent to which this occurred has not been evaluated). When these trees were 8 years old they were thinned by cutting 5 m wide strips (later reduced to 2.5 m) through the plantation. These timbers were sold in the local market and the revenue

Fig. 7.6 Design 2 (final crop trees under-planted beneath nurse trees) used at a degraded site in Vietnam. The *Acacia* overstorey has been under-planted with several native tree species able to produce high-quality timbers. The *Acacia* has facilitated the establishment and early growth of these but must be removed at some point when the advantages of facilitation are outweighed by the disadvantages of competition

was used to enlarge the *Acacia* plantation. Seedlings of a number of commercially valuable native species were planted under the *Acacia* canopy at densities of 200–500 tph (Fig. 7.6). These species included *Dipterocarpus alatus, Hopea odorata, Parashorea chinensis, P. stellata, Scaphium lychnophorum* and *Tarrietia javanica*. As these grew up more of the residual *Acacia* were gradually removed exposing the preferred species to full light. These trees could then also be sold to establish more of the plantation. Several hundred hectares of plantations have been established in this way.

One of the key silvicultural issues concerns the trade-off between the advantages and disadvantages of the nurse trees. These enable the preferred species to establish and survive but, at some point, they also begin to inhibit growth. This raises the question – just when should the overstorey cover be removed? This issue was addressed by McNamara et al. (2006) who related the mean annual increment of 8 year old trees of the under-planted species to the density of the overstorey *Acacia* trees amongst which they were planted. It was hypothesized that a strong relationship would imply the *Acacia* cover was affecting the growth of that species but any lack of a relationship would mean that growth was not yet being inhibited. The results showed that, at 8 years, high densities of *Acacia* trees had begun to inhibit the growth of the *Dipterocarpus alatus* while the height growth of other species such as *Hopea odorata* were still apparently unaffected (Fig. 7.7). Further monitoring

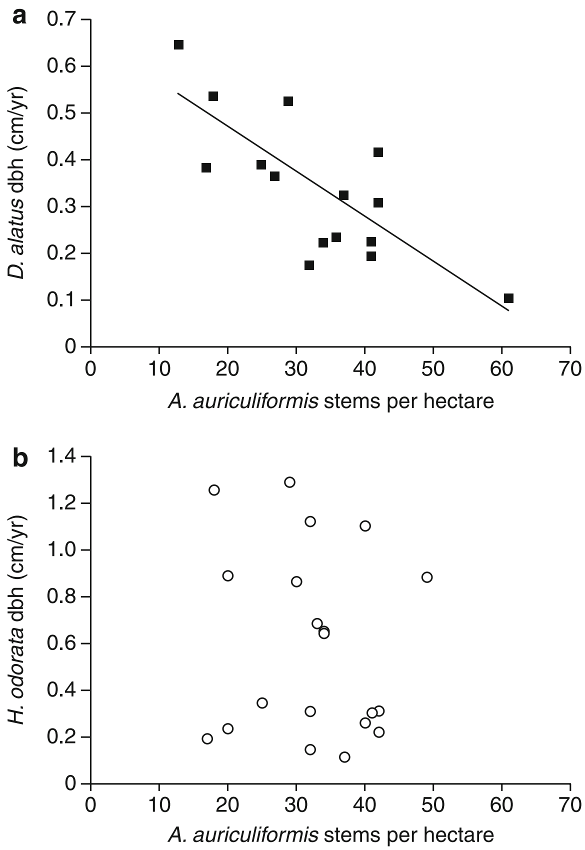


Fig. 7.7 Annual diameter growth increment (cm/year) of underplanted trees age 6–9 years planted beneath established *Acacia* overstories differing in tree density. (**a**) *Dipterocarpus alutus* – growth declines with increasing *Acacia* overstorey density ($p=0.0022$, $r=-0.7075$, $n=16$) and (**b**) *Hopea odorata* – no relationship between growth rate and overstorey density at this age (After McNamara et al. 2006)

will be needed to determine just when the final nurse trees should be removed. A similar approach has been outlined by Kuusipalo et al. (1995) for use at degraded sites in Indonesia.

Case Study 3: Improving conditions at a degraded site – Malaysia

Many dipterocarp species grow poorly when planted in open areas and appear to need some initial shade at the time of establishment. The Multi-storied Forest Management Project in Malaysia sought to establish whether various dipterocarp species could be established by planting seedling beneath a nurse crop (Anon 1999). The experimental plots covered 180 ha of *Acacia mangium* plantation which acted as a cover crop or nurse trees. At the time of underplanting these plantations were 4–5 years old and had a stocking of 900 tph. The *Acacia* were probably then more than 7 m tall (this height was not reported but is estimated on the basis of mean annual increment data). Five under-planting treatments were examined.

Each involved felling strips (i.e. rows of planted trees) through the *Acacia* plantation and planting the dipterocarps along these clearings. In treatment 1 alternative row of *Acacia* were cleared and replaced by a row of dipterocarp seedlings (1:1), treatment 2 removed and replaced every second two rows of *Acacia* (2:2), treatment 3 removed and replaced four rows leaving the next four rows (4:4), treatment 4 removed and replaced eight rows leaving the next eight rows (8:8) and treatment 5 removed and replaced 16 rows leaving the next 16 rows (16:16). These five treatments correspond with strips that were 3, 6, 12, 24 and 48 m wide. The single row (1:1) replacement left the new seedlings under canopy cover while the 8:8 and 16:16 strips essentially left the new dipterocarp seedlings as open plantings. A variety of dipterocarps were tested with each treatment involving measurement plots containing about 120 trees of each dipterocarp species. The strips were weeded and kept free of vines.

Most of the planted species had substantially lower survival levels (with many failing completely) as the width of the planting strips increased and seedlings were exposed to higher radiations levels. However, a few species (e.g. *Hopea odorata, Shorea leprosula*) were much less affected and were able to tolerate the more open conditions (Fig. 7.8). Tree height and stem diameters of all the surviving trees were much less affected by the strip width irrespective of species (Anon 1999).

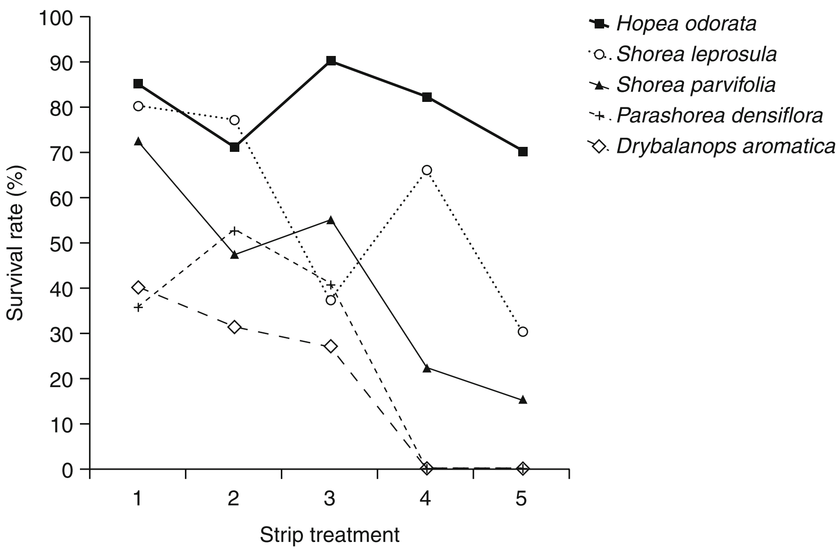


Fig. 7.8 Survival of trees planted in strips of various width cut through 3 year old *Acacia mangium* plantations in Malaysia. Treatment 1- strips were created by removing and replacing every alternate row of *Acacia* (1:1); Treatment 2 – remove and replace every alternative second two rows (2:2); Treatment 3 – remove and replace every alternative four rows while leaving four rows (4:4); Treatment 4 – remove and replacing every alternative eight rows while leaving eight rows (8:8); Treatment 5 – remove and replace every alternative16 rows while leaving 16 rows (16:16). Survival was measured 60 months after planting for *Shorea leprosula* and *S. parvifolia* and after 48 months for the other species (After Anon 1999)

The overstorey *Acacia* was removed after 8 year when these were 18 m tall. Care had to be taken in removing the *Acacia* to avoid damaging the dipterocarps. Because of this it was concluded that, at this age, underplantings in 12 m wide strips (the 4:4 treatment) represented an appropriate balance between providing enough overstorey cover to maintain survival while minimizing felling damage when the *Acacia* were removed.

Case Study 4: Reducing insect damage

The family Meliaceae includes some of the world's more valuable timber species but genera such as *Cedrela, Chukrasia, Khaya, Swietenia* and *Toona* spp. are frequently damaged by shoot borers from the genus *Hypsipyla* (Speight and Wiley 2001; Wormald 1992). In Australia, the growth of *Toona ciliata* (red cedar) is badly affected by *Hypsipyla robusta*. There have been many attempts to grow *Toona ciliata* (red cedar) in plantations because it's timber is so valuable but all have failed because of repeated insect damage to young shoots. Anecdotal evidence suggested damage is much less when the red cedar trees are grown in shade. Accordingly, a trial was initiated in north Queensland in 1941 using *Grevillea robusta* (another commercially attractive timber species) to create an overstorey or nurse crop for the *Toona ciliata* (Keenan et al. 1995). There were seven treatments in the trial. Treatment 1 was open-planted *Toona* established at 2,000 tph and treatment 2 was a mixture of *Grevillea* and *Toona* each planted at 1,000 tph. Additional *Grevillea* were also planted at this time in another five plots at a stocking of 1,000 tph. Then, over each of the next 5 years, *Toona* was planted among these additional *Grevillea* plots at a density of 1,000 tph. This led to a sequence of treatments in which *Toona* planted in the open, at the same time as *Grevillea* or beneath progressively older *Grevillea* trees creating a series of stands each with 2,000 tph. Some thinning of trees of both species was subsequently carried out over the following 50 years. Although the trial was unreplicated it has the advantage of being monitored over an unusually long period.

Insect damage was less and survival and tree form was best in *Toona* trees planted under the level of canopy cover provided by treatments 4–7 (Table 7.3). But this

Table 7.3 Growth of *Toona ciliata* at 54 years after being grown beneath a nurse crop of *Grevillea robusta* to reduce damage by the tip borer *Hypsipyla robusta* (Keenan et al. 1995)

Treatment	*Grevillea/Toona* planting dates	Age (year) of overstorey	Percent with multiple leaders	Average *Toona* stem volume m^3
1	–/1941	–	65	2.82
2	1941/1941	–	34	2.92
3	1941/1942	1	3	2.70
4	1941/1943	2	3	1.10
5	1941/1944	3	2	1.30
6	1941/1945	4	3	0.96
7	1941/1946	5	3	0.91

imposed a limitation on growth because of shading and individual *Toona* trees grew better as open-planted trees or if planted with the youngest *Grevillea* (treatments 1–3). For plantation managers the silvicultural compromise might be to create a temporary mixture by planting *Toona* beneath one year old *Grevillea* (treatment 3) and allowing the trees to grow tall enough to develop a commercially attractive tree bole. Thereafter the stand could be managed as a simple monoculture.

The obvious silvicultural question is how long to keep the beneficial overstorey before converting to a monoculture? There is some evidence that *Hypsipyla grandella* in Costa Rica mostly fly below 6 m (Grijpma and Gara 1970). This suggests any cover could be removed once the trees grew up and exceeded this height. But the behaviour of *Hypsipyla robusta* appears to be different and there is evidence that damage caused by this species also occurs in taller trees. One study of the effect of *Hypsipyla robusta* on *Toona australis* carried out in the Philippines, Thailand and Australia found damage continued as trees grew taller up to heights of 4.5 m and that height was a good predictor of damage (Cunningham and Floyd 2006). Although there was some indication that damage rates may have been then declining these authors also report other observations of damage being found on >35 m tall *Toona* trees. This suggests the best option for managers would be to retain cover trees until the *Toona* trees had reached a merchantable bole length.

The advantage of Design 2 is that it allows preferred species to be established at sites where they would fail if normal planting methods were used. But there are two disadvantages. The first is that the method requires a market price for small-sized logs of the facilitator or nurse species. The second is that there is usually a trade-off to be made between the ecological advantages provided by the facilitator and the inhibition it will eventually cause because of shading and root competition. The age at which this occurs will depend on the particular species involved and requires field trials with the species concerned to explore this trade-off.

The three case studies that used this design involved three different forms of facilitation including weed exclusion, the provision of shade for species unable to tolerate full sunlight at the seedling stage and changing the aerial micro-environments leading to reduce insect damage. Where *Acacia* were used there may have also been some improvement in soil nitrogen levels. In each case the facilitator species (*Acacia, Grevillea* spp.) might have been grown as a successful monoculture without the need for the complexities of mixtures but managers preferred to use these to enhance the quality of the goods being produced by the plantation. But the commercial value of the facilitator species also meant the mixture generated a cashflow before the final harvest of these preferred species.

Even-Aged Plantation Using Species Grown Together on Short and Long Rotations

This silvicultural system is represented by Design 3 in Table 7.1. Like Designs 1 and 2 it is also a temporary mixture and there are several versions of the design. In

one the primary purpose is to increase the financial attractiveness of a plantation containing commercially valuable but slow-growing sawlog species. This is done by planting a fast-growing species with the slower-growing species. The faster-growing species is harvested at an early age thereby providing a financial return while trees of the slower-growing species are able to continue growing until they reach their financially optimal harvesting size. The first harvesting operation also acts as a thinning operation.

Thinning in a monoculture plantation could obviously achieve the same outcome if a market could be found for the small-sized logs but this is often difficult. This system avoids such marketing problems by deliberately using a species able to provide a marketable product within the desired time period. As with any thinning operation, care is needed to ensure that harvesting does not damage the residual trees. In this system even more care is needed because the trees being harvested are larger than the residual trees. However, if row plantings are used it should be possible to minimize any damage because trees can be felled and removed along the rows. Some ecological complementarity between the species is needed to ensure the faster-growing species do not overly inhibit the slower-growing trees. But since the mixture is only temporary the extent to which this is required is probably a little less than in a permanent mixture.

A second version of the system is more concerned about using the species grown on the shorter rotation as a facilitator that fixes nitrogen and thereby boosts production of the preferred species. Ideally this nitrogen fixer should have a shorter longevity and it would also be advantageous if it was commercially valuable although this is not essential. The growth rate of the nitrogen fixer determines how the system is managed. If it grows quickly and over-tops the commercially preferred species then it may need to be thinned or removed. This assumes most of the nitrogen fixation has been carried out at an early age. If, on the other hand, it grows more slowly than the commercially preferred species if might be left to eventually senesce if it appears it is not affecting the growth of the overstorey species. In this case the death of these trees would also act as a stand thinning.

Case Study 5: Early cashflow from trees grown on short rotation – Vietnam

There is a strong market for sawlogs in many parts of rural Vietnam. But there is also a market for poles. A trial testing mixtures of trees able to produce both products was established at Doan Hung in Phu Tho province by the Forest Research Center (Lamb and Huynh 2006). Three native sawlog species (*Michelia mediocris, Canarium album* and *Chukrasia tabularis*) and *Eucalyptus urophylla* (for poles) were grown in alternate rows as pair-wise mixture of each species combination. The overall tree density was 1,100 tph. The eucalypt grew much faster than the other three species and after 3 years many trees exceed 9 cm diameter and 12 m

Fig. 7.9 Design 3 (trees with differing rotation lengths) used to grow *Eucalyptus urophylla* planted in alternate rows with *Michelia mediocris* in Vietnam. The plantation is now 4 years old. The eucalypt will reach a merchantable size within another few years and can be removed to generate a cashflow and reduce stand density. This will enhance the growth of the *Michelia* which will be grown until it reaches a sawlog size

height. These growth rates suggest the eucalypts will be saleable within another 2 or 3 years. This would leave the residual stand of sawlog trees with a stocking of 550 tph. Over the same time period the slower-growing native species achieved heights of 2 or 3 m and these are likely to be several meters taller by the time of the pole harvest (Fig. 7.9). Sufficient light penetrated the eucalypt canopy to reach their crowns and their growth was comparable with that when they were grown in simple monocultures. This particular trial is still too young to assess how the other species combinations will develop.

There was some indication that mixtures of the sawlog species with the eucalypt can improve tree form even at this early age. A sample of 20+ trees of each sawlog species in monocultures and mixtures found the mixtures induced reductions in the proportion of trees with forks (lateral branches >1 cm width arising below the main crown) or bends (a curve in main stem displacing it >4 cm within a vertical distance of 10 cm) and caused a small decrease in the average number of leading shoots in *Michelia* though not other species (Table 7.4). Of course many of these problems would normally be resolved by pruning or thinning the trees with poorer form but, nonetheless, the results indicate the potential power of the ‘trainer’ effect in these mixtures.

Table 7.4 Proportions or numbers of trees with forks and bends and average number of leading shoots in 4 year old trees of *Michalia mediocris, Chukrasia tabularis* and *Canarium album* when grown in mixtures with *Eucalyptus urophylla* of same age (Lamb and Huynh 2006)

	Michelia	*Chukrasia*	*Canarium*
Forks (%)			
Monoculture	21	35	51
Mixture	5	22	42
Bends (%)			
Monoculture	32	13	46
Mixture	14	7	33
Leading shoots (No.)			
Monoculture	1.13	1.26	1.55
Mixture	1.01	1.25	1.50

Case Study 6: Use of a nitrogen fixer to improve tree nutrition on infertile soils

Many eucalypt plantations in Australia are limited by nitrogen deficiencies. To test whether increasing proportions of a nitrogen fixer in a mixture might be able to improve productivity *Acacia mearnsii* was planted with *Eucalyptus globulus* in monocultures and in a replacement series in which the proportion of the two species varied but density remained constant (Bauhus et al. 2004; Forrester et al. 2004). The five stands included 100% eucalypt, 75% eucalypt + 25% *Acacia*, 50% eucalypt + 50% *Acacia*, 25% eucalypt + 75% *Acacia* and 100% *Acacia*. In the mixed-species stands seedlings of the two species were planted together in an intimate mixture along rows. Height growth was comparable for the first 6 years but thereafter growth of the *Acacia* slowed and the eucalypt became the dominant canopy species. The *Acacia* appears to have increased the height and diameter growth of the eucalypt in mixtures compared with those in the monoculture by increasing nitrogen availability through fixation and by increasing nitrogen cycling. There was no evidence that the improved nitrogen levels also improved the photosynthetic abilities of the eucalypt. Productivity also appears to have been enhanced because of the development of a stratified canopy with the eucalypt in the dominant position and the *Acacia* in the sub-canopy (Bauhus et al. 2004; Forrester et al. 2004). Best stand growth was recorded in the 50:50 mixture which, at 11 years, had more than double the biomass found in the eucalypt monoculture. Although the study is still comparatively young there are several silvicultural options open depending on markets. One of these would be to thin or remove all of the *Acacia* and leave the eucalypt to grow longer. If there were no markets for small trees the *Acacia* could be left and allowed to continue adding nitrogen to the system as the eucalypts continue to grow although it is not clear just how long the *Acacia* will continue to do this.

Even-Aged Plantation with All Species Grown Together in a Single Long Rotation

This silvicultural system is represented by Design 4 in Table 7.1. Unlike the previous designs this is a permanent mixture (Fig. 7.10). This design might serve several purposes. One might be to capture the potential for multi-species plantations to have higher levels of productivity than monocultures. It is not clear how many species should be used although the optimum number is unlikely to be more than three or four in plantations established primarily for timber production. Larger numbers than these would be more difficult to manage and the overall financial worth of the plantations is likely to be reduced as additional less-valuable species are included.

A second situation where this design might be used is when there is a need to increase the variety of products to diversify income sources or subsistence goods. Thus a plantation might include different types of timber trees as well as species able to supply various NTFPs (e.g., fruits, nuts, spices, medicines). It might even

Fig. 7.10 Design 4 (permanent tree mixtures) represented by a 60 year old mixture of hoop pine (*Araucaria cunninghamii*) and Queensland maple (*Flindersia brayleyana*) in sub-tropical Australia. The two species have similar growth rates but the hoop pine is more shade tolerant and has a deep crown while the maple is less shade tolerant and has a shallow crown

be possible to design such a plantation to include species able to supply such goods from a relatively early age thereby improving the timing of any revenue stream. These plantations could include only a few, or perhaps many, species.

Finally, a third situation where the design would be attractive is where certain ecological services are needed as well as goods. These might be to improve watershed protection (hence some deep-rooted species able to stabilize hillslopes might be included) or to sustain local wildlife (in which case food trees might be added to stands of commercial timber species) or even to increase the local populations of certain threatened plant species. In some of these cases the diversity of species used could be quite high even though some non-native species able to tolerate existing site conditions might have to be used.

A variety of spatial layouts could be used depending on the attributes of the species and the purpose of the mixture. In the case of commercial plantings of canopy species these might involve might alternative rows or belts of each species (Fig. 7.11a) or more intimate tree-by-tree mixtures along planting lines of two or more species (Fig. 7.11b). Mixtures might also be achieved by planting trees in small groups (Fig. 7.11c) or blocks (Fig. 7.11d). Over time such a block planting might be thinned to leave just one or two trees. Alternatively, where the objective of reforestation is the provision of ecological services and no future logging is expected, less care might need to be taken with spatial locations and trees of each species might be randomly located throughout the stand. In this case the emphasis might be more concerned with ensuring canopy trees are surrounded by several sub-canopy species.

The more complex the mixture, the more scope there is to involve a larger range of species and functional types. But, at the same time, the greater the complexity then the more uncertain the silvicultural outcome is likely to be. One advantage that multi-species plantings might have is in allowing growers to quickly screen a large number of possibly useful species to identify those able to tolerate site conditions and form stable mixtures.

a

A A A A A A A
B B B B B B B
A A A A A A A
B B B B B B B

A A A A A A A
A A A A A A A
B B B B B B B
A A A A A A A
A A A A A A A

b

A B A B A B A
B A B A B A B
B A B A B A B
B A B A B A B

c

A	B	C	G	D	C	H	G	F
D	E	F	X	F	B	D	X	B
G	H	X	E	H	A	A	C	E
B	E	G	A	F	X	H	G	C
X	C	A	C	D	E	A	F	B
H	F	D	B	G	H	B	E	X
A	B	C	G	D	C	H	G	F
D	E	F	X	F	B	D	X	B
G	H	X	E	H	A	A	C	E

d

A	A	A	B	B	B	E	E	E
A	A	A	B	B	B	E	E	E
A	A	A	B	B	B	E	E	E
C	C	C	D	D	D	F	F	F
C	C	C	D	D	D	F	F	F
C	C	C	D	D	D	F	F	F
E	E	E	A	A	A	E	E	E
E	E	E	A	A	A	E	E	E
E	E	E	A	A	A	E	E	E

Fig. 7.11 Different types of spatial arrangements for growing trees in mixed species plantings (**a**) two species planted in alternative single or multiple rows, (**b**) two species planted in more intimate mixtures (**c**) random mixtures of multiple species within small block plantings and (**d**) block plantings of a single species. Trees of different species are indicated by (**A**), (**B**), (**C**), etc.

Case Study 7: Mixtures involving Sandalwood and a host species

Sandalwood *(Santalum spp.*) is a hemi-parasite with around 16 species that are distributed across the Asia-Pacific region. It produces highly valuable timber with an aromatic heartwood although there are large differences in the oil content of timbers of the various species and genotypes. Natural stands have been heavily exploited for more than 100 years and many have been cleared or degraded. Natural regeneration can be assisted by broadcasting seed into natural stands where a variety of potential hosts already exist but less than 1% of these seed may produce seedlings. Because of this limited success rate alternative approaches are being explored.

The problem for those wishing to grow sandalwood is in finding an appropriate host (or facilitator) able to sustain the seedlings in the nursery and then later in the field. Several approaches have been developed. One is to grow the sandalwood in the nursery and to introduce a ‘pot host’. This is a host plant grown in the same pot or seedling tube. The pot host must be able to grow with the sandalwood and sustain it for as long as is needed (if the pot host dies the sandalwood will also perish) but not dominate it. The two must also grow together long enough in the nursery for the haustoria and root connection to be sufficiently robust to tolerate being transferred to the field and planted out. A variety of potential pot host have been tested but species of *Alternanthera* have often been used (Radomiljac 1998; Robson 2004).

Once in the field a new host is needed because the pot host, even if it was sufficiently long-lived, would be too close to the sandalwood and might overshadow it. This has been approached in several ways. One is to plant the sandalwood seedlings into old gardens sites or regrowth forest and allow the sandalwood to find a new host among the species already present. An alternative is to plant seedlings and a new host in alternate rows (or as alternative plantings along rows) such that the trees of the two species are within 2–3 m of each other. Under these circumstances the host may be parasitized within a year. Hosts used in field plantings have included *Casuarina equesitifolia* as well as species of *Acacia, Sesbania, Cassia, Dalbergia* and *Cathormium*. While a host with commercially attractive timber would be preferable some care is needed to ensure a balance is maintained between the sandalwood and host. Hosts with large spreading crowns may suppress the sandalwood (e.g. *Falcataria, Khaya* spp.). On the other hand, less vigorous hosts may succumb to competition from the sandalwood. It may even be necessary to use a third host to sustain the sandalwood through the rotation if the second host succumbs to such competition. Considerable skill is needed to select appropriate hosts and determine the numbers of these that should be used at any one time as well as the tree spacings to use. Some of the methodology being used to grow sandalwood in a large-scale industrial plantation in the dry tropics of northern Australia is outlined by Done et al. (2004) while current methods being used in smallholder operations in the Pacific are outlined by Ehrhart (1998) and Robson (2004).

Case Study 8: Mixtures involving pairs of commercially attractive tree species

A replicated trial was established in north Queensland to examine how several types of species pairs might interact (Huynh 2002). The species chosen were all local species and included *Eucalyptus pellita, Elaeocarpus grandis, Acacia aulacocarpa* and *Flindersia brayleyana*. The first two species are relatively fast growing and shade-intolerant species while *Flindersia brayleyana* grows less quickly and is relatively more shade tolerant. The *Acacia* usually grows well and is a putative nitrogen fixer under appropriate field conditions and is usually regarded as intolerant of shade. These four species were grown in pair-wise mixtures with trees of each species planted in alternative rows as well as in monoculture plantings where each species was planted was bounded by rows of itself. Overall tree density in both the mixtures and monocultures was 1,100 tph. The site was an old sugar cane farm and receives about 2,200 mm rain. As expected, the fastest growth was observed in trees of *Eucalyptus pellita* and *Elaeocarpus grandis.* After 38 months these reached 13.5 and 12 m respectively in monocultures while the *Flindersia* reached 8 m and the *Acacia* reached 7 m.

Growth of each species was statistically similar in mixtures and monocultures except for *Eucalyptus* which had significantly better growth when mixed with *Flindersia* than when grown in a monoculture. These two species appear to have formed a stratified canopy and be a complementary pair. The *Eucalyptus* also had a larger leaf area per tree, probably a consequence of the greater space available to its trees in the upper canopy layer. The leaf area of *Flindersia* was similar in this mixture and in a monoculture. When expressed as volume there was evidence that the Relative Yield Total of the *Eucalyptus-Flindersia* mixture at this age was greater than could be obtained in the respective monocultures (Table 7.5).

By contrast *Eucalyptus pellita* had much poorer growth when mixed with *Elaeaocarpus*. The height growth rates were similar and there was no sign of complementarity in the canopy architecture of the two species or of canopy stratification.

Table 7.5 Relative Yield Total in stand volume of pair-wise mixtures of *Eucalyptus pellita (EP), Elaeocarpus grandis (EG), Flindersia brayleyana (FB)* and *Acacia aulacocarpa (AA)* at 38 months after planting. A Relative Yield Total >1.0 shows production is greater than would occur in a monoculture (Huynh 2002)

	Relative yield of			
Mixture	First spp.	Second spp.	Relative yield total of mixture	Conclusion
FB + EP	0.73	0.89	1.62*	Benefit
FB + AA	0.71	0.77	1.48	
FB + EG	0.51	0.66	1.17	
AA + EP	0.47	0.78	1.25	
AA + EG	0.47	0.63	1.10	
EP + EG	0.50	0.35	0.85	Failure

*Gain is significant ($P < 0.05$)

The Relative Yield Total of this mixture was <1.0. There was some evidence that *Eucalyptus* might form complementary mixtures with *Acacia* because of the difference in growth rates allows some canopy stratification but *Acacia* is not tolerant of much shade and the growth differences (between the mixture and the monocultures of each species) were not statistically significant. There was also some indication that the *Flindersia – Acacia* mix might have some advantages but, again, the mixture was not significantly better than monocultures of its component species. Overall, the trial supports the idea that species with complementary crown structures forming stratified canopies may form productive mixtures.

Case Study 9: Multi-species plantings involving four species; Costa Rica

Many farmers in Costa Rica grow small timber plantations on their farms (Piotto et al. 2003a). Despite this there is little understanding of the most appropriate species to use or the silvicultural requirements of these species. A series of mixed species plantations were established to explore how a variety of native tree species grew in plantations and whether greater levels of production could be achieved in monocultures or in mixtures (Petit and Montagnini 2006; Piotto et al. 2003b). Three of these trials were established in the humid lowlands at La Selva and used four species grown in monocultures and together in mixtures. Each trial included a putative nitrogen-fixer, a relatively fast growing species and a relatively slower growing species. All of these species were chosen because they are widely used by small farmers in the region and because they provided a variety of branching patterns, sizes and crown shapes. Planting density was originally 2,500 tph (i.e. 2 m spacings) to accelerate interactions between trees. Half of each trial was thinned at 3 and 6 years while the other half was left unthinned. Each trial suffered some mortality reducing the number of species in Trials 1 and 2 to three species each.

By age 10–11 years different results were found in each trial as a consequence of the particular species used. In Trial 1 two of the three species grew better in the mixture than they did in the monoculture (the exception being *Calophyllum brasiliense* which is a relatively slow-growing species normally found in mature forests). In addition, the survival rate of all species was also better in the mixed. In Trial 2 there was no difference in the growth of trees of the various species planted in monocultures or mixtures although, once again, survival rates were higher in the mixed stand than in the monocultures. In Trial 3 there was no difference in the growth of species planted in the mixtures or in monocultures except for *Genipa americana* which was suppressed in the mixture and grew much better in monocultures.

The trials highlighted the superior performance of *Vochysia guatemalensis, Terminalia amazonia, Jacaranda copaia* all of which are relatively fast growing species representative of early or mid successional stages. The two slower growing species from later successional stages (*Calophyllum brasiliense* and *Dipteryx panamensis*) could grow in mixed plantation mixtures but tended to be

suppressed by the faster-growing species. Tree mortality and the loss of several species complicates these analyses. Although there is some evidence for enhanced productivity in Trial 1 it is difficult to know the nature of the mechanisms that have produced it and it may be that the better growth of the faster growing trees (*Jacaranda copaia* and *Vochysia guatemalensis*) was at the expense of the slower growing trees (*Callophyllum brasiliensis*). If so the gain was largely due to competition causing a reduction in the effective density of these trees rather than any degree of complementarity between the species remaining in the mixture.

Case Study 10: Multi-species planting involving 16 species

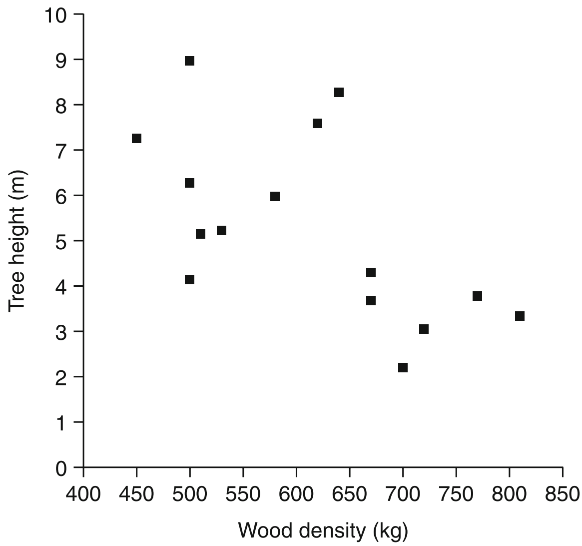
This trial was established to explore the growth in plantations of a variety of rainforest tree species in sub-tropical Australia at a time when little was known of the silvicultural characteristics and site requirements of most of these species. The 16 species included in the trial all had high-quality timbers but there was considerable variation in their properties and their timber densities ranged from 400 to 800 kg m^{-3}. The species included shade-intolerant secondary species as well as shade tolerant species representative of more mature successional stages. They also included hardwoods and softwoods. Most species came from nearby rainforests although several exotic species were also used (e.g. *Khaya nyasica, Cedrela odorata*). The plantation was established at a sub-tropical location in southern Queensland that has moderately fertile soils and receives around 1,500 mm of rain. Prior to being planted the site was used as a cattle pasture.

The layout of the trial ensured that trees of each of the 16 species were surrounded by those of at least three, and more commonly four, other species. This was done by planting a single tree of each species at random within a block of 16 trees (4 × 4) and each block was surrounded by similar adjoining blocks (Erskine et al. 2005b). The layout resembles that shown in Fig. 7.11c. Trees were spaced 3 m apart and all trees were planted at the same time. Most species grew well in the first few years and canopy closure occurred after 4–5 years.

At 5 years of age the trees ranged from 2.8 to 9.0 m height and there was evidence of several canopy layers developing. Given the differing ecological characteristics of the various species it was expected that species believed to be from early successional stages would form the upper canopy while those thought to be representative of more mature successional stages would form a subordinate canopy layer. But the limited knowledge of the growth rates of the various species in a plantation setting meant it was hard to predict how each species would fit within the evolving plantation structure. Several hypotheses were developed. The first was that height growth is closely related to timber density and all those species forming the upper canopy should have low timber densities (Whitmore 1984). This was indeed the case although the r^2 value was only 0.487 (Fig. 7.12). None-the-less, the relationship provides an indication of what to expect in terms of relative growth rates.

The second hypothesis was that the slower growing and shade tolerant species would form a sub-ordinate canopy layer beneath that produced by the fast-growing

Fig. 7.12 Relationship between height (at 5 years) and timber density for 15 tropical tree species growing in a mixed-species plantation in sub-tropical Queensland



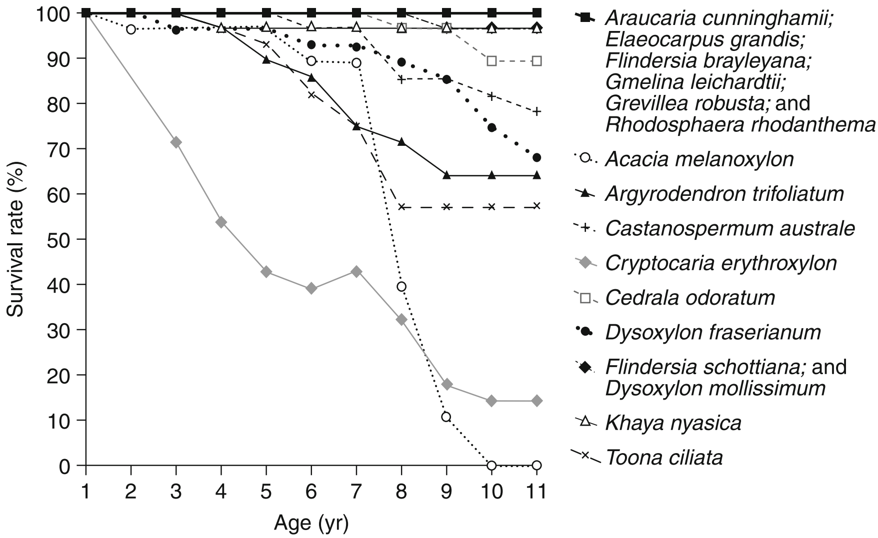


Fig. 7.13 Survival over time of species planted in the even-aged mixed-species plantation shown in Fig. 7.12. The mixture includes mostly native species from early and late successional stages although the exotics *Cedrela odorata* and *Khaya nyasica* are also included

secondary species. This also occurred but not nearly to the extent expected. In fact the survival rates of some supposedly shade tolerant species was poor (e.g. *Cryptocarya erythroxylon*) although they appeared to have stabilized after 10 years (Fig. 7.13). The reason for this is not entirely clear but it may be that in some locations the overall light levels in the unthinned plantation are simply too low to sustain these species. Even more surprising was that *Acacia melanoxylon*, one of

the fastest-growing species that occupied the upper canopy layer, also began dying after about 7 years. Many were infected by various stem borers and bracket fungi. This species normally has a longevity of around 40–50 years in this region but may have been growing below its preferred altitudinal range.

The third hypothesis, based on result reported by Keenan et al. (1995), was that open-grown trees of *Toona ciliata*, an indigenous member of the Meliaceae, would be damaged by the tip borer *Hypsipyla robusta* but that surviving trees would grow well once they were shaded by the faster-growing early secondary species. In fact many of the *T. ciliata* died and the survivors grew poorly although other exotic Meliacea in the plantation including *Khaya nyasica* and *Cedrela odorata* grew well with only limited insect damage. This presumably reflects the fact these are less susceptible to this particular *Hypsipyla* species. This result confirms that planting *T. ciliata* in the open within a species mixture is not a useful method of growing this species at this site (c.f. Case Study 4).

The planting was able to identify timber tree species able to grow well at this particular site and has also produced a structurally complex multi-species plantation. With time plantations like this might provide habitats for a variety of species and so contribute to local biodiversity conservation. But the ability of mixed plantations to provide goods (e.g. timber) and ecological services (e.g. wildlife habitats) depends on how they are managed as the trees grow larger and competition increases. This is discussed further below.

Case Study 11: Planting mixtures of non-commercial species to create stable and self-sustaining new forests

As mentioned earlier, not all mixed-species plantings are established to generate commercial outcomes. In some degraded sites the motive is simply to develop resilient, species-rich communities of trees and shrubs that are able to tolerate the site conditions and be self-sustaining. This approach might be especially useful at highly degraded sites where changes to environmental conditions make it difficult to restore the original vegetation and where some form of rehabilitation (as defined earlier) is a more appropriate choice. These types of plantings can be especially useful at former minesites. Hobbs et al. (2009) referred to these plantings as 'novel ecosystems' because they involve species combinations and relative species abundances that have not occurred before in that particular biome.

An example of the approach is at the tailings dump at the Kidston gold mine in northern Australia. The area is occupied by tropical woodlands and has a strongly seasonal climate; the total rainfall is 720 mm but 80% falls between November and April meaning there is a long dry period. The topsoils at this site were mostly alkaline with pH levels ranging from 7.7 to 9.7 (c.f. 6.9 in nearby unmined areas). Because of this the objective of revegetation was to establish a self-sustaining community of trees, shrubs and ground cover with a structure resembling that of the pre-mining woodland rather than attempting to restore the original community (Roseby et al. 1998). Around 30 trees and shrub species were use together with a

number of local and introduced grasses. All were selected on the basis of their capacity to tolerate the climate and soil conditions. The tree and shrub species used were all native species (though not necessarily species previously growing at the site) and these were initially introduced as seedlings. The species used include at least three families (Myrtaceae, Mimosaceae and Casuarinaceae or Proteaceae depending on the particular site being revegetated) and up to five genera. All species were planted in equal numbers. None of the species were commercially important and there was no intention to carry out any form of harvesting. Trees were planted at 5 m spacings (i.e. 400 tph). After 3 years all species had survived although survival rates varied from 17–95%. A number had also fruited and seedlings of several species had become established on the ground beneath the tree canopy. Having identified those species best able to tolerate the site conditions research has subsequently sought to develop methods by which these can be established by direct seeding rather than as seedlings in order to reduce costs. The amount of seed used was adjusted according to viability and germination success in order to establish roughly similar populations of each species. Monitoring is carried out to verify that composition, tree density and ground cover targets are being met. Most local species are poorly dispersed and none of those in the surrounding natural vegetation have yet colonized the site although this may occur in the longer term.

These five case studies using Design 4 fall along a gradient of increasing uncertainty. Past experience has given silviculturalists a good deal of information about the nature of the species mixes needed to grow sandalwood (Case Study 8). But the other four examples involve increasingly larger numbers of species and more uncertainties about outcomes. This might not matter in cases such as mine site rehabilitation where some losses can be tolerated provided sufficient species remain to provide a stable community (Case Study 11). But it is a wasteful approach in situations where a commercial benefit is required. The pair-wise comparison (Case Study 9) might be a useful approach to identifying complementary species when something is known about the attributes of each species while the mixes involving four and 16 species (Case Studies 10 and 11) might be useful when knowledge about site tolerances, growth rates and shade tolerances is more limited. But can these sometimes ad hoc assemblages be replaced by mixtures composed of species known to be complementary with each other because of the way they use resources?

Identifying Ecologically Complementary Species

As noted earlier, complementarity can come from species having different growth phenologies and using resources at different times or by having differing canopy or rooting architectures and so using resources from differing spatial locations. Two highly shade intolerant species are unlikely to form a complementary and commercially viable mix because one will eventually overtop the other and out-compete it. On the other hand, a mixture of a relatively shade tolerant species and a shade

intolerant but open-crowned species, both of which are able to grow at much the same rate, could be complementary and grown together because of their contrasting tolerances and abilities to partition space. Examples of both outcomes were observed in Case Study 8.

Much depends on the longevity of the shade-intolerant species and the length of the proposed rotation. If the upper canopy species is not able to persist until the end of the rotation then care needs to be taken to accommodate the changing densities and spatial patterns that its disappearance will cause. Ashton et al. (2001) suggest shade intolerant species should be planted to surround tolerant species and short-lived pioneers should surround longer lived species to take account of complementarities in resource usage and in self-thinning among species. The spacings between trees should reflect known crown morphologies. Over time, the short-lived species will die and the soil and light resources they have used are taken over by slower growing shade tolerant species which ultimately form the canopy. The proposals depend heavily on knowledge of tree longevities, maximum tree sizes and shade tolerance.

Classifications such as shade-tolerant or shade-intolerant are necessarily superficial descriptors of species attributes and imply that a dichotomy exists when there is really a continuum, especially at the post-seedling stage. While acknowledging the idea of a continuum Poorter et al. (2006) identified four functional types among adult trees. In the case of trees of small stature these included (i) short-lived (<30 years) shade-intolerant pioneers and (ii) shade tolerant species able to establish and survive in the shade. Among trees with larger stature were (iii) long-lived (>30 years) pioneers that are shade intolerant and (iv) partially shade-tolerant species that can establish in the shade but need light to grow. Based on this classification the upper canopy layer should have the long-lived pioneers while the partially shade-tolerant species are candidates for the sub-dominant canopy positions. Shade intolerant species tend to have narrow and shallow crowns. They also have a rapid leaf turnover and are grow rapidly in height. More shade-tolerant species tend to have deeper and broader crowns with longer-lived leaves. They are better at capturing light in patchy or variable light environments but under appropriate conditions may be able to grow as fast in height as narrow crowned species. This led Poorter et al. (2006) to suggest that species with a range of crown allometries can probably co-exist in the upper canopy. As noted earlier, the maximization of timber productivity is not always the primary objective of mixed-species plantations. This means there may be considerable scope for assembling relatively stable mixtures of species able to occupy the sub-dominant canopy position based on crown attributes and, perhaps, wood density (as a surrogate index of growth rate).

Empirical field trials and further studies in natural forests will eventually generate knowledge of the species traits necessary to make more informed judgements about the species needed to create these types of plantations. In the meantime an alternative approach to identifying compatible species to use in the sub-dominant strata might be to identify those having a similar response to the competition they experience when planted in a mixture. In this case the hypothesis would be that two

species with similar competitive abilities should form a stable mixture because both intra-and inter-specific competition is similar.

A large number of Competition Indices (CI) have been developed that might be used for this purpose (e.g. Biging and Dobberton 1992, 1995; Burton 1993; Vanclay 2006a). Some of these are distant-dependent indices meaning they take account of the spatial patterns of trees while others are distance independent indices that do not. Most assess the growth of the subject tree (e.g. height, diameter, crown development) in relation to the growth of surrounding trees. One simple version of such an index is shown in Fig. 7.14a. In this case the trees were established in a mixture using a regularly spaced, square planting grid and growth of the subject tree is related to the algebraic sum of the differences in it's height (h_i) and that of each of the four surrounding trees (h_j).

$$CI = \sum_{j=1}^{n} \left(h_i - h_j \right)$$

By assessing the CI of a number of trees of the subject species in a plantation mixture it is possible to examine how growth is affected by competition. Figure 7.14b, c show an example where *Erythrophloeum fordii* is much less sensitive to being overtopped by surrounding neighbours than *Canarium album* which suffers when surrounded by taller neighbours. The slope of the relationship is an index of the sensitivity of that species to competition from surrounding trees. Other things being equal, compatible species able to form stable mixtures are those with similar slopes. This approach was used to identify potentially compatible species for use in plantation mixtures in sub-tropical Queensland (Huynh 2002; Lamb et al. 2005). Such indices are necessarily simple measures of the competitive abilities of particular species because growing conditions and competitive relationships change as trees age and root systems extend. Other more complex measures have been used that take account of larger numbers of surrounding trees and their distances from the subject tree. For example Vanclay (2006a, b) used:

$$CI = \sum \left(H_j / H_i \right) / \text{Distance}_{ij}$$

Using this index and the SIMILE modeling environment he was able to explore inter-actions in a young plantation containing a mixture of *Eucalyptus pellita* and *Acacia peregrina*. The index helped identify the optimal proportions of the two species in the mixture, the spacings that might be used and the spatial layout. This analysis suggested it did not matter whether the species were planted in alternative rows or as alternative trees along rows. Vanclay (2006a, b) argued the approach has the advantage of overcoming problems of unexpected tree mortality and any differential effects that tree density might have on species in the mixture.

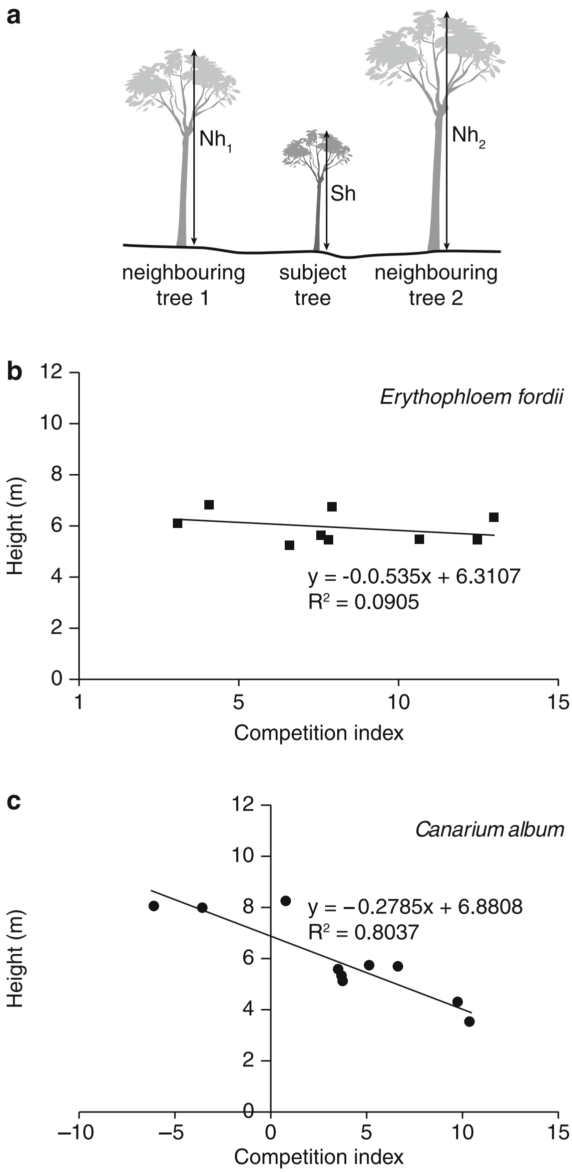


Fig. 7.14 Competition indices can be used to assess the relative competitive abilities of different species. (**a**) the competition experienced by a tree is represented by the algebraic sum of the differences in height between the target tree and each of the four neighbouring trees (**b**) the heights of *Erythrophoeum fordii* trees are not related to differences in the value of the competition index suggesting it is tolerant of some competition (**c**) the height growth of *Canarium album* declines sharply as the competition index increases suggesting it is more sensitive to inter-specific competition (Lamb and Huynh, unpublished data)

Some Management Issues

Mixtures are inherently more difficult to manage than simple monocultures and this is one of the reasons they are less popular amongst large-scale forestry enterprises even though some designs offer the possibility of increased productivity. But these additional management inputs may not be a major disincentive for other land managers, including smaller growers, and many of these may have already used mixtures in previous agroforestry practices on their farms. For such landowners the need for additional management inputs may be outweighed by the advantages of mixtures including the greater product diversity, improved timing of cashflows and reduced risk. Nonetheless there are a number of management issues such farmers must confront depending on the type of mixture that is being used.

The Number and Type of Species to Use

One early management decision that must be made is the number of species to be used. Some mixtures may involve only a small number of species such as when a NTFP crop is grown in the plantation understorey (Design 1) or where one tree species is grown on a short rotation and mixed with another growing on a longer rotation (Design 3). In such cases the mixture may only involve two species. But other mixtures may use rather more species such as when a single nurse species is used to facilitate the establishment of a number of other higher-value species planted in the understorey (Design 2) or when a permanent mixed-species stand is established (Design 4). In these cases the number and type of species could be substantially greater. The choice of just how many species to use clearly depends on the circumstances and objectives of the grower establishing the plantation. Only a relatively small number of carefully selected species might be used where the objective is enhanced production or income diversification but rather a large number may be needed to provide certain ecological services.

The type of species is also important. In addition to being able to tolerate site conditions they must be able to facilitate or complement each other and some must be able to produce certain goods (e.g. timber, fruit, resins) for which there is a known market. But, they should also contribute to building resilience. Diaz and Cabido (2001) and Elmqvist et al. (2003) suggest there is a benefit from including a variety of functional types as well as some diversity within these types but there may be a limit to just how much diversity plantation managers can cope with. Perhaps the best that might be done is to aim to use species able to tolerate the environmental stresses most likely to occur in the lifetime of the plantation (e.g. nutritional stress, drought, wildfire). There may be rather more scope for adding diversity and building resilience at a landscape scale rather than at every site and this will be discussed further in Chapter 10.

A second issue arising from this first one concerns the relative proportions of each species or species-type that should be used. Apart from Smith's (1986)

suggestion that overstorey trees should not exceed 25% of the total stand there are few other guidelines for practitioners. In most cases the decision is one that must also take some account of the financial implications of the choice and most landowners will favour the most commercially attractive species. But functional effectiveness does not necessarily mean species must be present in large numbers and just a few trees of ecologically attractive species such as wildlife food or even rare or endangered species added to a new plantation might provide significant functional or conservation value at a relatively low cost to production.

Thinning

All closely spaced plantations eventually require thinning if they are not to stagnate. As noted in Chapter 5, thinning can be done 'from above' or 'from below'. Thinning from above is normally not practiced in monocultures since it leaves behind a genetically impoverished stand to grow over the duration of the rotation. But this disadvantage does not necessarily apply in mixtures and a form of 'thinning from above' is integral to Design 2 involving the temporary nurse trees and also to Design 3 where the faster growing species is removed to generate an early cash-flow while leaving trees of the more valuable species to grow through and form the final crop. All of these thinnings reduce stand density, alter competitive relationships and leave more space for the crowns of the residual trees. The chief problem with this type of operation is that it can damage the smaller residual trees. This damage can be reduced if trees are planted in rows so that trees are felled and successively removed along a row. Removal of canopy trees also means that substantially more light is able to reach the ground so that care may needed once more to control weed growth until the residual trees are able to close their canopies.

The more commonly practiced 'thinning from below' removes smaller, less vigorous trees as well as those with poor form. Again, it alters competitive relationships and the trees left behind are then those best-suited to take advantage of the improved growing conditions (e.g. more light and less root competition) provided by thinning and to grow into high-value logs. In principle it is equally applicable in mixed species plantations such as those created using Design 4. But, putting aside the question of whether or not the timber produced by thinning can be sold, the issue for the manager is whether to allow thinning to remove only slower growing trees, irrespective of their identity, or whether to retain some trees because of their future market value or even for the sake of maintaining a certain level of biodiversity? The answer clearly depends on the grower's objectives. Some landholders establish mixed-species plantations for production and 'conservation' purposes without being entirely clear about which is most important. This dilemma highlights the need to have quite explicit management objectives.

An illustration of some of the trade-offs that might be made comes from a desktop study using data from the plantation described above in Case Study 9. In this case 16 species had been planted at the same time in a random mixture in an

endeavor to create a plantation that might provide some conservation benefits as well as sawlogs although all the trees of one species had died and been lost from the mixture. by age 10 years the overall planting density was 1,100 tph. Over a period of 15 years some species had grown rapidly and become canopy dominants, others became sub-dominants while others had been suppressed or died. By this time the canopy height of this unthinned stand was around 20 m and some of the larger trees had diameters exceeding 30 cm dbh.

A variety of thinning prescriptions were explored to investigate how thinning might affect species richness but no attempt was made to anticipate the financial impact of thinning (Erskine et al., 2005a). The prescriptions included (i) a simple mechanic thinning that removed every second (diagonal) row of trees thereby halving the density but maintaining an even spacing between all tree, (ii) removing trees with poor form irrespective of the impact on stand species richness, (iii) removing all trees unable to provide a straight bole exceeding 5 m length irrespective of the impact on species richness and (iv) removing all trees with small stem diameters, again irrespective of the impact on species richness. A final treatment (v) involved testing the effect of removing the canopy dominant *Elaeocarpus grandis* which has a large crown and which is beginning to suppress adjoining trees (i.e. a thinning from above).

The effect of these different prescriptions on residual species richness, stand basal area, residual stocking and overall stem form is shown in Table 7.6. All treatments reduced the basal area although the greatest reduction came from the mechanical thinning of every second row and the loss of the dominant *Elaeocarpus* had only a modest impact. The greatest effect on residual stocking was thinning to remove trees without a >5 m bole while tree form was, unsurprisingly, most improved by the treatment that sought to do so. Both of these prescriptions also reduced the basal area by more than 40% meaning that competition has probably been reduced to the point which should allow an appreciable increase in the rate of growth. Perhaps surprisingly, species richness was not greatly affected. The greatest impact came from the treatment removing the smaller trees but, even then, 12 of the original 15 species still remained (although the magnitude of any reduction

Table 7.6 Effect of differing thinning prescriptions on the attributes of a 15 year old mixed species plantation (Erskine et al. 2005a)

Prescription	Basal area $m^2\ ha^{-1}$	Residual stocking tph[a]	Average tree form[b]	Species richness
Pre-thinning	32.1	843	6.2	15
Remove every second row	15.5	417	6.2	15
Remove trees of poor form	19.4	440	7.8	15
Remove trees without straight bole length >5 m	17.0	330	7.3	12
Remove trees with small dbh	29.5	538	7.2	13
Remove the canopy dominant	23.8	773	6.1	14

[a] Trees per ha
[b] Tree form based on a ten point scale (one poor and ten good)

obviously depends on the threshold size used). Removing the dominant *Elaeocarpus* would reduce overstorey competition but the treatment had less immediate impact on basal area or on the average form of the residual trees than might have been expected.

In short, it appeared it is probably possible to develop thinning prescription which may involve several of these strategies which boost tree quality, stand growth and still retain much of the original species richness. It remains to be seen how the various types of species in such a plantation might be able to respond to such treatments over time and what the overall financial consequences of the treatments could be. Of course different forest growers will have different objectives and so make different trade-offs. For many smallholders the primary value of species richness is in the diversity of goods it generates and therefore in its insurance value. Such growers are likely to strike a balance that is different from those more interested in conservation issues and the provision of ecosystem services.

Rotation Length

The longevity of the plantation rotation can be based on the biological rotation (the time needed to maximize the timber yield before growth rates begin to decline) or the financial rotation (the time needed to optimize the present net return on capital invested). In most industrial monocultural plantations all trees are felled at the end of the rotation and the site is replanted. But having a pre-determined rotation length is probably less important for growers attracted to using mixed-species plantings. Some may follow industrial growers and clear-fell after a certain time. Others may adopt an opportunistic attitude whereby individual trees are removed according to the needs of the moment or as market opportunities present themselves. Regeneration might be carried out after clear-felling to produce a second even-aged mixed-species planting. Alternatively, some growers may decide to plant in the canopy gaps left after a tree is removed creating an uneven-aged stand. The situation can be complicated by natural regeneration. Wormald (1992) quotes Muttiah (1965) who describes a plantation established in Sri Lanka early in the twentieth century containing an even-aged mixture of *Swietenia macrophylla*, *Tectona grandis* and *Artocarpus integrifolius*. This was established to facilitate the establishment of the *Swietenia* which would have otherwise been damaged by insects. After 60 years many of these trees had reached >78 cm diameter and were felled. But large numbers of *Swietenia* seedlings regenerated beneath the residual canopy and the forest was gradually converted to an uneven-aged, mixed-species stand. Of the trees in the new forest only 20% were *Tectona grandis* or *Artocarpus integrifolius*.

Rotations are important when goods such as timber are being produced but are less relevant when the objective is to produce ecosystem services. In cases where payments are made for ecosystem services the advantages of clear-felling may disappear and mixed-species stands may be managed using some kind of selection system or logging may even be abandoned (e.g. Case Study 11).

Mixtures at a Landscape Scale – a Mosaic of Monocultures

The discussion hitherto has concerned mixtures at particular sites. But diversity can occur at a variety of scales ranging from individual sites to landscapes. Mixtures at this larger scale may be represented by a number of small monocultural patches of each species scattered in a mosaic across the landscape. The obvious advantage of this patch mosaic is that the establishment and management of these monocultures relatively simple. On the other hand, the variety of environmental conditions present across the landscape allows different species to be carefully matched to their most appropriate sites. Taken together, the overall plantation area can then generate a wider variety of forest products than a simple monoculture.

The ability to create these types of mosaic depends on land ownership patterns. In landscapes containing large numbers of smallholders there will be a natural tendency for the development of many small forest plantations within an agricultural matrix although landowners with poorer soils and steeper sites are more likely to plant trees than those with uniformly good soils. Once a species becomes popular it is likely to dominate plantings throughout a district. But, even so, many farmers continue to plant a variety of species. One survey involving 45 households in the Philippines found farmers had planted 126 premium species and a further 36 non-premium species on their farms as well as 74 species of fruit trees (Emtage 2004). Another survey in northern Vietnam that found 64 tree species had been planted at 37 farms (Lamb and Huynh 2006). Nibbering (1999) and Pasicolan et al. (1997) have reported similar findings. In the longer term this diversity of species may have some economic as well as ecological advantages.

The situation is different when landholdings are larger. In this case the prospective plantation owner(s) may decide to have a mosaic of monocultures across their plantation estate rather than an extensive monoculture using one species because it will allow particular species to be matched with their most appropriate sites. But several questions need to be resolved. First, what proportion of the landscape should be reforested? Secondly, how might the non-plantation matrix be managed? And, thirdly, what should be the size of individual forest patches? The type of landscape being reforested and its spatial heterogeneity will determine the answers to all of these questions. In a mostly agricultural landscape the trees might be established in areas unsuited to cropping. In a badly degraded forest area the plantations might be located on the more accessible areas with the remaining land being allowed to develop natural forest regrowth. In both cases the spatial distribution of land suitable for crops or plantations determines the proportions reforested and the area of forest patches. But other issues might influence these decisions as well. Spatial mosaics can be attractive for conservation reasons, especially when steep lands are reforested and riparian strips are protected. In such cases the extent of plantings and the way areas outside the plantation are managed may be strongly influenced by the need to protect watersheds or provide conservation corridors for wildlife.

An example of a deliberate attempt to create a spatial mosaic of different monocultures comes from Shandong province in China where foresters are

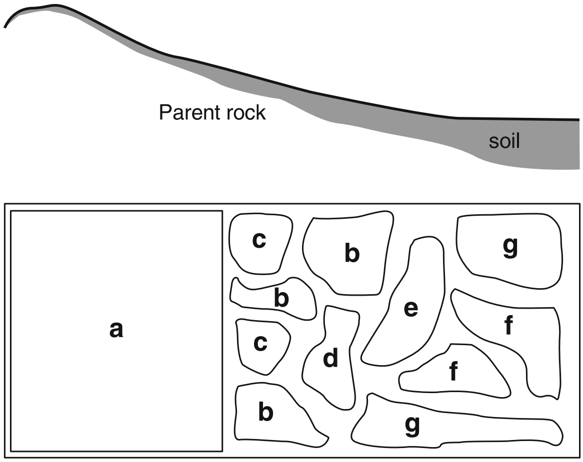


Fig. 7.15 Design 5 (mosaic of monocultures) showing a spatial mosaic of monocultural plantings on a degraded hillslope. Only a few species (**a**) can tolerate sites on ridgetops with shallow soils. Soil depth increases at lower topographic positions widening the number of species that might be planted. Species (**b**) and (**c**) can be used at mid-slope positions but (**d**), (**e**), (**f**) and (**g**) are used at locations with deeper soils and more favourable conditions. These monocultures are planted in patches embedded in a matrix of natural regeneration

establishing 'eco-forests' on severely degraded hills. There is considerable variability in environmental conditions across these landscapes. Soil depths are shallow at the tops of hills and only a few species can tolerate the exposed site conditions. Soils are deeper on lower slopes and environmental conditions are more favourable allowing a wider variety of species to be used. Extensive monocultures are used on the most exposed hilltop sites using the few species able to tolerate these sites. On lower slopes patches of different species up to a maximum size of 2 ha are used. These patches are separated by belts of other species to form a complex spatial mosaic. An example of the approach is shown in Fig. 7.15 and an illustration of mosaic plantings being applied in practice is shown in Fig. 7.16.

The issue of how to foster tree planting at a landscape scale and design spatial layouts to improve the environmental outcomes is discussed in more detail in Chapter 11.

Providing Ecosystem Services

The variety of silvicultural designs used in mixed species plantings mean that some are not very different from simple monocultures in their ability to conserve biodiversity and supply various ecological services while others are substantially better. The larger the number of tree species involved then the greater the difference is likely to be.

Fig. 7.16 Design 5 (mosaic of monocultures). A landscape mosaic achieved by growing small monocultural patches of each species at appropriate sites. In this case about six tree and shrub species are represented on the landscape

Biodiversity

Multi-species plantations are likely to have greater structural complexity than monocultures and so make the plantations more attractive to some wildlife species. One study of multi-species timber plantations in tropical Australia compared the biodiversity present in young (age 5–15 years) monocultures and mixed-species plantations and found both types of plantations attracted a variety of birds, lizards and mites but most were habitat generalists and only a small proportion of these were 'rainforest' species (Kanowski et al. 2005). Nearby 'restoration' plantings aged 6–22 years had higher numbers of birds, including rainforest specialists and lizards, though mite species numbers were similar to those in the timber plantations. Part of the reason for these differences is almost certainly the fact that the mixed species timber plantations used less than 20 tree species while the 'restoration' plantings had up to 100 tree species. This would have affected structural complexity and possibly also food resources. The value of this study is constrained, however, by the relatively young age of the trees and a different pattern emerges as the plantations become older.

Much greater levels of plant diversity were found in older (40–70 years) timber plantations growing in the same area. These were originally established as

monocultures but had been colonized by additional tree species from nearby natural forest. This converted simple monocultures to structurally complex and species-rich mixtures. Keenan et al. (1997) found as many as ten woody species in could be present in 78.5 m^2 plots. Overall there were 155 tree species and a total of 350 plant species across the 151 plots sampled in the survey. This diversity created habitats and conditions making the plantations more attractive to wildlife and Kanowski et al. (2005) found they had almost 75% of the birds found in intact rainforest and comparable numbers of lizard and mite species.

One of the more widely studied forms of mixed-species planting are the shaded coffee plantations in which coffee is grown as an understorey beneath a tree cover. A variety of different planting designs have been used and some in Central America contain significant numbers of vertebrates and invertebrates (Perfecto et al. 1996; Somarriba et al. 2004). Again it appears that the more structurally and floristically diverse these are, then the greater their value for biodiversity conservation. The few studies of shaded coffee plantations in Asia suggest these support rather less biodiversity than those in Latin America (Philpott et al. 2008). This may be because of their simpler structure and much lower levels of overstorey shade or because the particular canopy trees used provided little food for native birds.

The complex agroforest systems of southeast Asia represent a particular type of multi-species planting. In many of these a small number of tree species dominate the canopy layer but there can be a species-rich understorey. Thiollay (1995) studied so-called jungle rubber (*Hevea brasiliensis*), damar (*Shorea javanica*) and durian (*Durio zibethinus*) agroforests in Sumatra and found all had large numbers of bird species present although fewer than were found in nearby undisturbed natural forest. Overall about 40% of the birds recorded in natural forests were missing from the agroforests. Those absent were the larger frugivores and insectivores and forest interior specialists. Similar results were reported by Beukema et al. (2007) who found the species richness of terrestrial pteridophytes was higher in rubber agroforests than in nearby natural forest while the numbers of bird species was comparable and the numbers of epiphytic pteridophytes and vascular plants were lower. There were fewer species of birds and pteridophytes with more specialized habitat requirements in the agroforests than in natural forests.

These observations suggest mixed-species plantations have the capacity to improve regional conservation outcomes in landscapes where patches of residual natural forest remain. Their ability to do so will depend on factors such as the overall canopy architecture and on the food resources available. The wildlife species most favoured will be the habitat generalists rather than the habitat specialists although the longer the plantations remain and the more plant colonists they acquire the more attractive the habitat conditions are likely to be for these habitat specialists. But the landscape context is important and plantings close to residual forest patches are likely to more effective in supporting the conservation of biodiversity than more isolated plantings. Mixed-species plantations may be especially useful in providing a buffer zone around natural forest patches and, for some wildlife species at least, corridors between such patches. Mixed species plantations

can also add heterogeneity to landscapes and so help mobile seed dispersers. Any plantation logging will, of course, substantially alter these new habitats but the impact this has on the newly acquired biodiversity will depend on the scale and location at which it is done. These issues will be discussed further in Chapter 11.

Soil Protection and Hydrological Flows

The capacity of plantation monocultures and secondary forests to protect watersheds has been discussed in previous chapters. In principle, the ability of mixed species plantations to conserve soils and protect watersheds is likely to be better than most monocultural plantations and may, in some cases, approach the levels of protection found in secondary forests. This is because of the multiple canopy layers present in most mixed-species plantations in comparisons with the single canopy layer in monocultures. This was confirmed in studies reported by Zhou et al. (2002) which found substantially less erosion in structurally complex mixed-species plantation in China than from simple monocultures. Note, however, that in many cases it is the herbs, shrubs and small trees growing close to the ground in the understorey that are important rather than the diversity of canopy trees.

In the case of hydrological flows the difference between monocultures and mixed-species plantations may be smaller. Hydrological flows depend on rates of evapo-transpiration and the infiltration capacity of surface soils. Simple mixtures may not differ very much from monocultures although species-rich and structurally complex mixtures may intercept more rainfall and so generate less run-off. A study by Zhou et al. (2002) found this to be the case in a comparison of interception and stemflow in a eucalypt plantation and a nearby mixed species plantation and run off and stormflow were less in the mixture than in the monoculture.

As with all reforestation programs, the success of any mixed-species plantings in improving soil protection and hydrological functioning depend on the landscape context in which it is carried out and this will be discussed further in Chapter 11.

Carbon Sequestration

Mixed species forests, like monocultures, can absorb and sequester large amounts of carbon both above and below ground. The carbon content of above-ground biomass is closely related to stand biomass so that mixtures with enhanced productivity are likely to also have enhanced carbon uptake. Most comparative studies have been carried out at relatively young ages when small differences in plantation age lead to large differences in the amounts of carbon sequestered. Perhaps the more interesting question is whether *older* mixed-species plantings sequester more carbon than monocultures of the same age. At these ages the relative contribution of species with low-density and high-density timbers is likely to be changing depending on their proportions in the original mixtures and on their

longevities. Large differences between mature monocultures and mixtures might emerge if these species with high timber densities have been advantaged by being grown in a mixture. But differences in the way the two types of plantations are likely to be managed – thinning schedules, clear-felling or selective logging – make it difficult to know if older mixed-species plantings do have any real advantage over monocultures of the same age. For all practical purposes, the differences between the two systems may be small.

There is some evidence that larger amounts of carbon are sequestered in soils by mixed-species plantings than by monocultures. One study found enhanced levels of soil carbon accumulated over time in mixtures involving three tree species and two monocots compared with the amounts found in monocultures of the individual tree species (Russell et al. 2004). Root growth tended to be greater in mixed species plantings than in monocultures suggesting this was the source of the additional carbon. However, there was also evidence that beyond a certain production threshold, it was the chemistry of the detrital input, most especially that from roots, that was responsible for increased levels of soil carbon rather than the amount of root material.

Other studies have shown that more soil carbon accumulates in plantations involving nitrogen fixing species (Kaye et al. 2000; Resh et al. 2002). This appears to be due to a slower rate of decomposition of older recalcitrant soil carbon as more nitrogen is fixed. Mixtures of a nitrogen fixing species with other non-nitrogen fixing species can sometimes yield higher rates of carbon sequestration both above- and below-ground than monocultures of either species (Kaye et al. 2000). Further work is needed to explore just how mixtures, but especially those involving nitrogen fixers, might be designed and managed in order to optimize above-ground and soil carbon sequestration.

Conclusions

Mixed-species plantings offer landholders some potentially significant advantages over plantation monocultures despite their greater management complexity. Depending on the type of mixture used, these advantages include their capacity to produce a variety of goods rather than just one product and their ability to generate a wider variety of ecosystem services and conservation values than monocultures. In addition they are sometimes able to facilitate the establishment of commercially preferred species at highly degraded sites and to generate an early cashflow thereby making tree-growing a more attractive land use option for many smallholders. Although much of the research carried out on mixtures has concerned whether or not they have higher levels of productivity than monocultures it is these other issues that are more likely to induce many landholders to adopt mixed-species plantings.

But random species assemblages and *ad hoc* plantings are unlikely to generate these benefits and there are, as yet, no simple recipes or blueprints to follow. The two key elements underpinning most successful mixtures are facilitation and

complementarity. In some situations enough will be known of the attributes of commercially attractive species to make preliminary judgements about their complementarity with other species. Differences in crown architecture and growth phenology are useful starting points. In such cases pair-wise comparisons may be a useful way of testing these combinations. But otherwise it may be useful to use larger numbers of species in mixtures and learn from experience, accepting that some failures will certainly occur.

Most commercially-focused growers will probably use only small numbers of species in mixtures. This is to prevent management becoming too complex and to avoid the contribution from the most valuable species being diminished by other, less economically attractive species. Simple mixtures can probably be managed using some form of thinning followed by a clear-felling and replanting. More complex mixtures may end up being selectively logged and eventually becoming uneven-aged stands.

All mixed-species plantations involve making some form of trade-offs. These might involve the numbers or proportions of different types of species used, the balance between managing for production or managing for conservation or the ways in which thinning is carried out. In some situations the final outcome may be one that suits no one and it may be that some trade-offs are easier to manage at a landscape scale rather than at every site. This will be discussed further in Chapter 11.

A distinction was drawn earlier in Chapter 4 between Rehabilitation and Ecological Restoration. Mixed-species plantings that involve some (tolerant) exotic species may be the best way of reforesting some highly degraded sites but there will always be some situations where the preferred choice is to try to re-establish only native plant species and to attempt to restore the original ecosystems. This is discussed in the next chapter.

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